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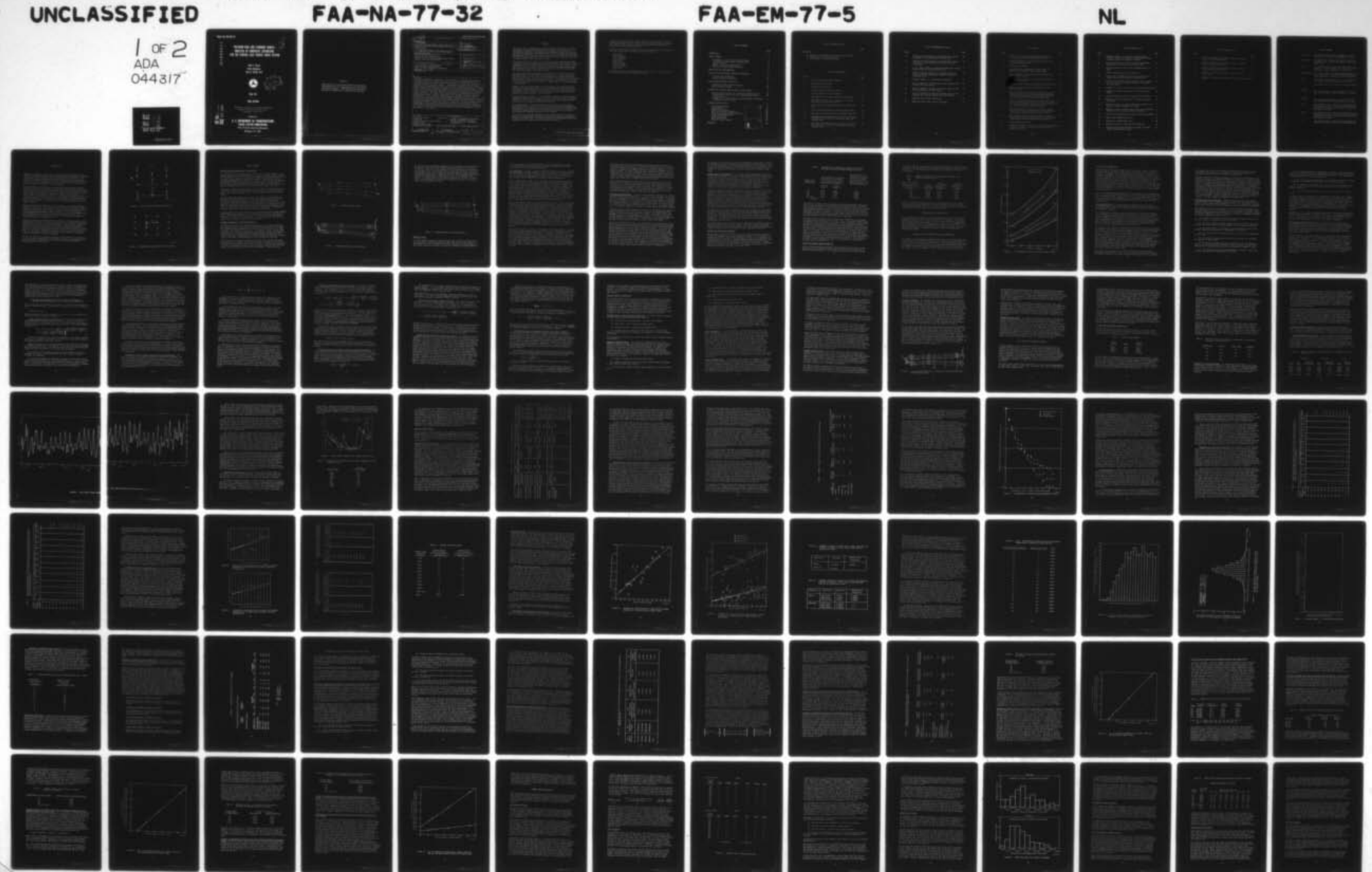

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COLLISION RISK AND ECONOMIC BENEFIT ANALYSIS OF COMPOSITE SEPARATION FOR THE CENTRAL EAST PACIFIC TRACK SYSTEM

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JUNE 1977

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16. Abstract

This report presents an evaluation of the application of composite separation to the Central East Pacific (CEP) track system. Criteria for the evaluation were a collision risk and an economic benefit's comparison of the existing four-route and proposed composite six-route systems. A 6-month data collection was performed. Radar data from land-based facilities in California and Hawaii and from Ocean Station Vessel November were processed to determine aircraft navigation performance. Utilization of the existing system was gauged from air traffic control facility data, and flight crew survey forms were used to collect information necessary for comparative analysis purposes. The report describes estimation of collision risk model parameters from the data. Lateral, longitudinal, and composite collision risks were estimated for the existing and proposed composite systems based upon accepted North Atlantic Systems Planning Group (NAT/SPG) methodology, while vertical collision risk was calculated based upon previous NAT/SPG studies. Lateral collision risk for the proposed composite system was found to be lower than for the existing structure. Comparisons of fuel burn and flight times indicated that the proposite composite system would be more economically beneficial than the existing route configuration. As a result of the study, the proposed composite system was recommended for implementation on a trial basis.

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PREFACE

The authors wish to acknowledge the cooperation and contributions of the many individuals and organizations which made it possible for this study to be undertaken and completed; in particular, the cooperation of the users of the system, both commercial and the United States Air Force (USAF), for completing and submitting the flight crew survey forms and also for providing flight plans and other pertinent information for the economic benefit study. The USAF also provided the mobile radar unit used at Pahoa.

The Western and Pacific Regions of the Federal Aviation Administration (FAA) cooperated fully by providing flight history information and controllers' manual measurements of aircraft deviations at the exit from the track system. Also, the Western Region cooperated by providing the system analysis and recording tapes, and the Pacific Region supplied technicians to monitor the automatic data recording equipment installed in Hawaii.

The authors gratefully acknowledge the contributions of Mr. John E. Parry of the FAA's Office of Systems Engineering Management. Mr. Parry, under whose sponsorship this study was done, provided guidance and coordination without which the effort would not have been accomplished. Furthermore, Mr. Larry Billow of Air Traffic Services is acknowledged for his excellent program support and overall FAA coordination which contributed significantly to the accomplishment of this program.

Members of the Systems Development Branch, Simulation and Analysis Division, at National Aviation Experimental Center (NAFEC) participated in design and installation of the data acquisition systems used at Pahoa, Honolulu, and on Ocean Station Vessel November. They also manned the data collection system onboard ship during the data collection period.

The Applied Physics Laboratory of Johns Hopkins University is acknowledged for supplying the TRANSIM System, used to accurately fix the position of November, and the U.S. Coast Guard is commended for their cooperation during the data collection period onboard the ocean station vessel.

The United Kingdom and the Netherlands provided a guide for the technical methodology for the risk and cost analysis through their previous analytical work relating to the North Atlantic organized track system. In addition, they provided the computer program for the risk model and took time to assist in resolving several problems encountered in the program.

The United States Government/Industry Working Group provided the coordination between the aforementioned organizations and the FAA, making it possible to obtain the necessary data. They also coordinated in the planning and provided necessary review at numerous intervals during the project.

Princeton University provided valuable support by participation in the data reduction and smoothing of track data in the North Atlantic Systems Planning Group (NAT/SPG) model analysis and also in the economic analysis of the Central East Pacific (CEP) track system.

The NAFEC project team was comprised of the following members of the Analysis Branch who participated in various phases of the project:

Allen Busch
Brian Colamosca
John Vander Veer
Dale Livingston
Wayne Smoot
Edward Kobialka
Robert Holladay
Jeffrey Krupnikoff
Linda Hartz

The authors also wish to acknowledge their appreciation to the many others who participated in the numerous supporting tasks.

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LIST OF SYMBOLS

λ_x, λ_y, λ_z	The metallic length, width, and height of a typical aircraft in the oceanic track system under study.
S_x, S_y, S_z	The longitudinal, lateral, and vertical separation standards in the parallel-route oceanic track system under study.
$P_r(L)$	The probability that two aircraft with planned separation, L, in r^{th} dimension will overlap in the r^{th} dimension, r being y (lateral) or z (vertical).
E_r(same/opp)	The occupancy associated same-direction/opposite-direction aircraft pairs for the r^{th} planned separation, r being y (lateral), z (vertical), or yz (composite).
$\overline{\lvert\Delta V\rvert}$	The average along-track speed of an aircraft pair as all planned longitudinal separation, L, is lost.
$\overline{V}$	The average speed of an aircraft in the track system.
$\overline{\lvert\dot{y}(L)\rvert}$	The average relative crosstrack speed of an aircraft pair as all planned lateral separation, L, is lost.
$\overline{\lvert\dot{z}(L)\rvert}$	The average relative vertical speed of an aircraft pair as all planned vertical separation, L, is lost.
$E_x(t)$	The probability that a same-route, same-flight level, same-direction aircraft pair has initial along-track separation of exactly t minutes after correction for mach number differences
$P_x(t)$	The probability that a same-route, same-flight level, same-direction aircraft pair loses initial along-track separation of exactly t minutes after correction for mach number differences
π_x	The probability that a same-route, same-flight level, same-direction aircraft pair overlap longitudinally

INTRODUCTION

During the latter part of the 1960's and the early 1970's, steadily rising numbers of commercial flights coupled with the military exigencies in Southeast Asia placed a heavy burden upon the Central East Pacific (CEP) air traffic control (ATC) system route structure between San Francisco/Los Angeles and Honolulu. The burden resulted in delays to system users in obtaining desired routes as well as the assignment of users to flight levels and routes which were not optimum with respect to fuel utilization.

After assessment of the problem, the United States proposed that composite separation be evaluated as a means of increasing system capacity and providing a greater number of economically attractive routes and flight levels for track system users. This separation technique, providing for the addition of routes midway laterally and vertically between the already existing routes of a track system, is illustrated in figure 1, which shows a cross-sectional view of a composite structure. In the figure, S_y is the planned lateral separation between coaltitude traffic, and S_z is the planned vertical separation between flight levels of a route. A cross-section of a conventional track system is shown in figure 2.

This report covers the analytical study of the merit of introducing composite separation into the CEP. The study, requested by the Federal Aviation Administration's (FAA's) Air Traffic Service, was performed in the National Aviation Facilities Experimental Center (NAFEC) in support of the FAA's Office of Systems Engineering Management. This study was carried out in accordance with the commitment made by the United States during the International Civil Aviation Organization's Asia/Pacific Regional Air Navigation Conference held at Honolulu, Hawaii, in September 1973.

Composite separation procedures were first adopted in the North Atlantic (NAT) organized track system in 1971 and successfully relieved operational congestion in that area. Acceptance of composite separation in the NAT track system was based upon studies conducted by the North Atlantic Systems Planning Group (NAT/SPG). The studies focused upon the impact of composite separation in two areas: (1) safety, as measured by the risk of midair collision, and (2) economic benefits. The NAT/SPG methodology developed for these two areas was adapted to the CEP environment in order to investigate the feasibility of applying composite separation in the CEP track system.

The next two sections of this report present a general summary of the results of the study and recommendations arising from the results. Subsequent sections present detailed descriptions of the collision risk and economic benefits analyses carried out for the CEP.

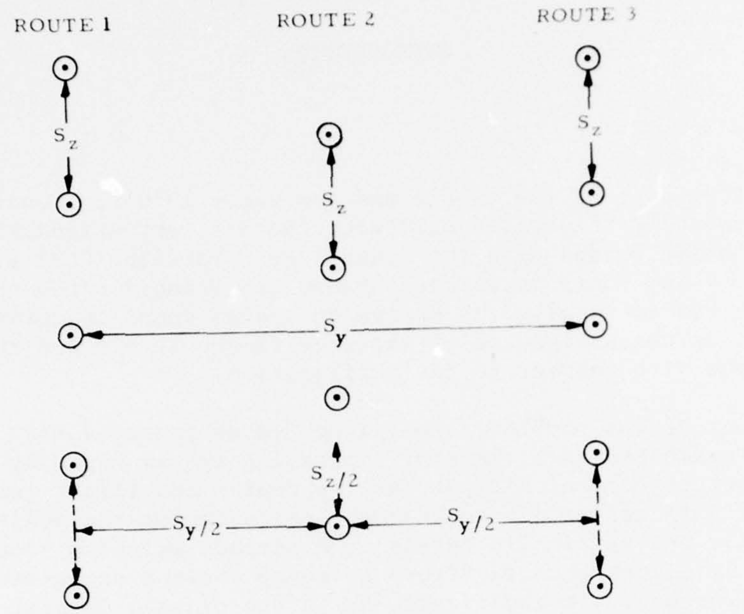


FIGURE 1. TRACK SYSTEM WITH COMPOSITE SEPARATION

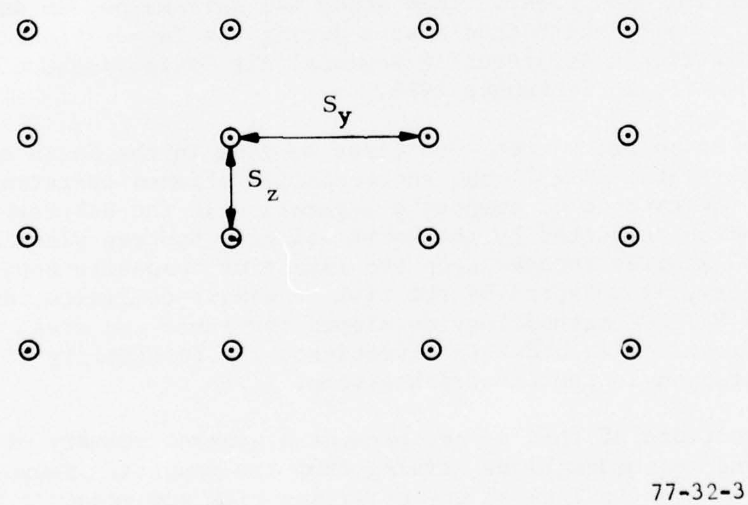


FIGURE 2. CONVENTIONAL AND COMPOSITE TRACKING SYSTEMS

GENERAL SUMMARY

DESCRIPTION OF THE EXISTING CEP TRACK SYSTEM.

The configuration of the existing CEP track system is shown in figure 3. The system consists of four routes North, Alfa, Bravo, and South, which operationally provide two route pairs: North/Alfa, connecting San Francisco and Honolulu, and Bravo/South, joining Los Angeles and Honolulu. North and Alfa routes reasonably approximate great circle arcs between the San Francisco and Honolulu areas; however, Bravo and South routes each have about a 9° turn near the midway point between Los Angeles and Honolulu, with the resultant effect that the two southern routes do not as closely approximate great circle arcs.

The lateral separation between adjacent routes in the track structure varies as a function of location in the system, but is a minimum of 100 nautical miles (nmi). The interpair separation grows to larger than 215 nmi at the eastern termini.

Two same-route, same-flight-level aircraft are separated from each other by a minimum of 20 minutes upon entry into the track system, unless both aircraft are assigned mach number spacing. In this case, initial separation is 15 minutes if both aircraft have the same mach number, 10 minutes if the first aircraft's mach number exceeds that of the second by 0.03, and 5 minutes if the first aircraft's mach number is 0.06 greater. Eastbound and westbound operations are conducted on each route at alternate flight levels. Flight levels utilized on any route are separated vertically by 2,000 feet.

A United States Coast Guard cutter serves as Ocean Station Vessel (OSV) November and is nominally positioned at 140° W longitude midway between Alfa and Bravo routes. The vessel's primary functions are search and rescue, and weather observation. However, the ship does have a search radar which can track aircraft on all four routes in the vicinity of 140° W.

ALTERNATIVE COMPOSITE SYSTEM CONFIGURATIONS.

As originally conceived, the proposed CEP composite track system consisted of the existing structure and separation standards with the addition of a compositely separated route between the two routes of each route pair, as is shown in figure 4 and referred to as system A. The composite routes, called Victor and Yankee, are positioned midway between the routes of a pair, and available flight levels on a composite route are staggered midway between the flight levels of the pair. Longitudinal and vertical separations within the composite route are identical to those employed in the existing route structure.

During the study, alternative composite structures were proposed, and after much analysis, the composite route structure shown in figure 5 and referred to as system B was synthesized and studied in detail. This track system appeared to be more advantageous than the originally proposed composite structure with respect to both collision risk and cost effectiveness. Since each route

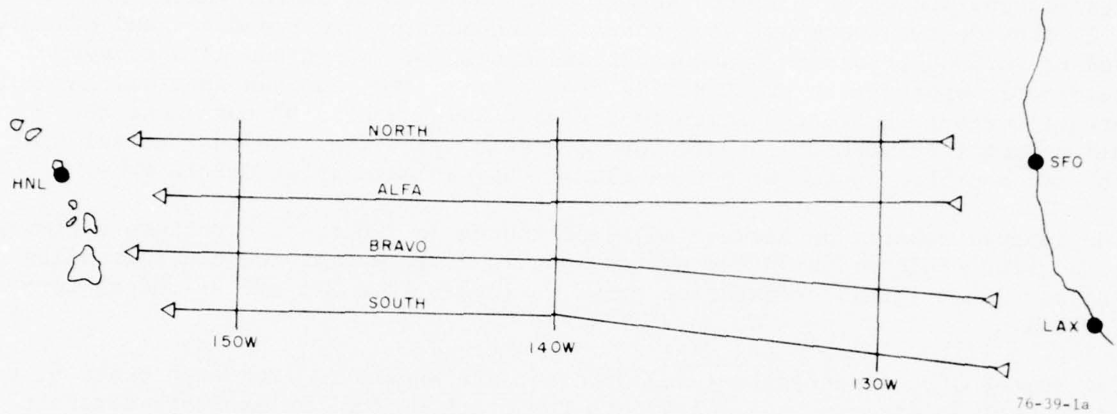


FIGURE 3. EXISTING CEP TRACK SYSTEM

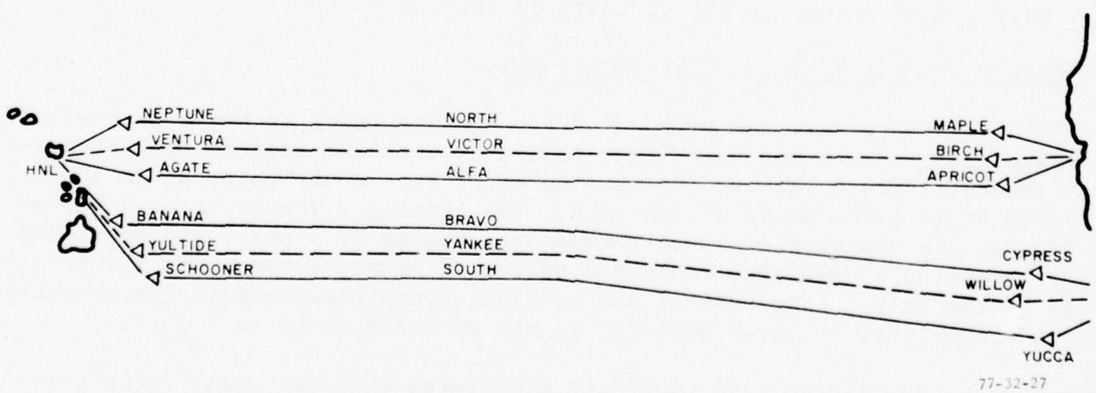


FIGURE 4. PROPOSED COMPOSITE CEP TRACK SYSTEM A

in this system was compositely separated from its laterally adjacent neighbors, the lateral collision risk was expected to be lower than that of system A. In addition, since each of the southern triad of routes more closely approximates a great circle route between Southern California and Hawaii than do the corresponding routes in the originally proposed composite system, additional cost savings should accrue. The dogleg at 140° W in the southern routes of the existing CEP permits radar coverage of all routes by OSV November when on station. In consideration of the scheduled phase-out of the OSV on June 30, 1974, no advantage would be realized by retaining the southern route heading changes in any composite structure.

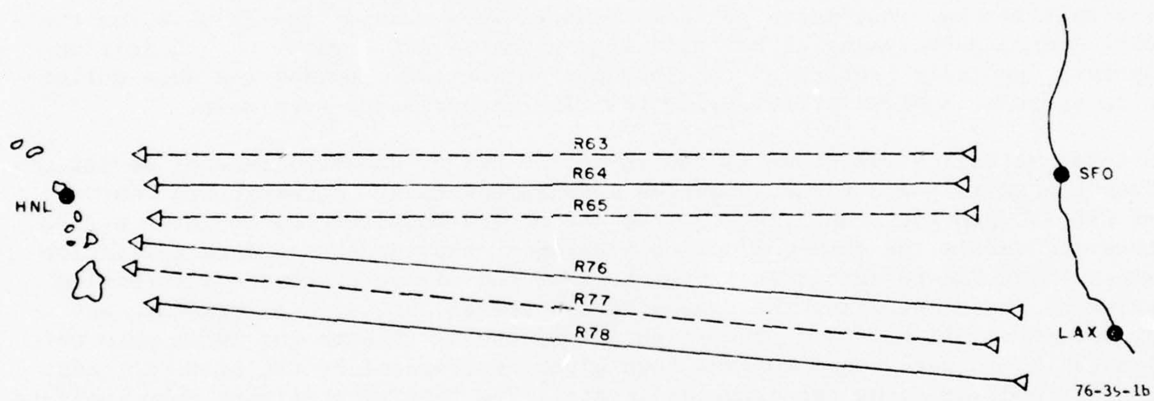


FIGURE 5. PROPOSED COMPOSITE CEP TRACK SYSTEM B

METHOD OF STUDY.

The study program consisted of three primary areas of work: (1) a data collection conducted to provide information on CEP track system operation and to develop the data base necessary for subsequent analyses, (2) an assessment of the relative levels of collision risk for the existing and proposed composite

CEP track systems, and (3) a determination of the cost advantage to system users engendered by the implementation of composite separation in the CEP. Each of these areas is now briefly discussed.

DATA COLLECTION. In order to provide information required to perform collision risk and economic benefits analyses, a data collection was carried out in the CEP from December 15, 1973, to June 30, 1974. The data were of four types: (1) aircraft position measurements, (2) ATC facility data, (3) flight crew survey forms, and (4) commercial and military flight planning data.

Position measurements of CEP aircraft were made using secondary surveillance radars (SRR's) at five locations: the Oakland, Los Angeles, and Honolulu air route traffic control centers (ARTCC's), as well as aboard OSV November and at a special mobile radar installation at Pahoa on the Island of Hawaii. The measurements were of two types, manual and automatic. Manual measurements were estimates of aircraft lateral deviation from assigned course made by air traffic controllers observing radar displays at the ARTCC's. Automatic measurements were time-sequenced digitized radar target reports describing aircraft tracks. Automatic position reports were made at the ARTCC's, on the OSV, and at Pahoa using either existing automated ATC devices or acquisition systems specially fabricated for the data collection. During the data collection program, approximately 19,500 position measurements were made.

Special attention was given to the large (30 nmi or greater) lateral deviations from course in the aircraft position measurement data. A committee, composed of CEP ATC providers and track system users, investigated the 96 large errors observed during the data collection program at the land-based data collection sites. The FAA requested that operators of the aircraft provide information relevant to ascertaining the causes of the errors, and such information was provided for all but 14 of the flights. Of the 82 flights for which data were available, 10 were found to have been given reclearance by ATC prior to radar contact and were thus not large deviators. The remaining flights were analyzed by the committee and causes for the deviations were determined. The committee's findings were that 79 percent of the deviations were caused by flight crew errors, 15 percent by onboard equipment failures, and 1 percent by weather. The committee could find no explanations for three of the lateral errors, and one of these was removed from the large deviator data set after subsequent analysis.

ATC facility data were collected at the Oakland and Honolulu ARTCC's. The data consisted of flight progress strips and other records concerning all flights in the CEP during the data collection period. Information on approximately 18,000 flights was gathered. The data for each flight consisted of such items as aircraft type and flight number, assigned route and flight level, and times across required reporting points while enroute. ATC facility data for each of the flights was transferred to computer and analyzed in order to determine route and flight level utilization, aircraft and user mix in the track system, and daily traffic loadings. In addition, the ATC facility data were processed to extract certain information required for the collision risk and cost benefit analyses.

The flight crew survey form was designed to provide certain information not available from any other source. Of particular interest were the route and flight level desired and actually obtained by a flight (a measure of the CEP's ability to respond to user demand) and onboard navigation equipment in use during a flight. The intent during the data collection program was that each flight would file a flight crew survey form. Because of certain problems in distribution and notification, 54.2 percent of the CEP flights actually filed a form. Of those flights responding, approximately 10 percent indicated that either the desired route or flight level was not obtained.

Flight planning methodology and data were obtained from several CEP track system users in order to provide a basis for the economic benefit analysis. For each type of aircraft encountered in the CEP, the flight planning data contained the list of preferred routes and flight levels between Los Angeles or San Francisco and Honolulu. Also included were data descriptive of fuel burn characteristics and expected flight times for each aircraft type as a function of flight level, season of the year, and payload.

COLLISION RISK METHODOLOGY. Collision risk methodology based upon the pioneering work of Peter Reich (references 1, 2, and 3), has as its goal the calculation of an objective level of safety assignable to a track system. A collision risk can be computed for each of the planned separations (lateral, longitudinal, vertical, and composite, if applicable) in a track system. The collision risk for a planned separation is defined as the expected number of midair accidents in 10 million track system flying hours due to the loss of the planned separation. It should be noted that one midair collision equals two midair accidents.

Collision risk methodology assumes that there is no independent surveillance of aircraft positions on the track system. Collision risk methodology further assumes that the track system under study consists of parallel routes, that ATC makes no errors in the assignment of aircraft to the routes, and that aircraft initiate no collision avoidance maneuvers. Certain other assumptions are made regarding the independence of single aircraft and aircraft pair navigation errors which are listed in the main body of the report.

Collision risk methodology results in a mathematical model which relates parameters descriptive of separation standards, navigation performance, and proximity of aircraft pairs to the expected number of accidents in 10 million track system flying hours due to the loss of planned separation. For each of the planned separations, the model takes on a different mathematical form. The parameters descriptive of navigation performance and aircraft pair proximity must be estimated from information taken in the structure under study: hence, the requirement for the previously described data collection in the CEP. The NAT/SPG has concentrated upon developing the methodology for assessing and monitoring the risk of collision due to the loss of planned lateral separation, as a result of the experience that the lateral is the largest in magnitude of the estimated collision risks. Thus, emphasis in the CEP study has been upon the lateral collision risk, but the estimated collision risks due to the loss of the other planned separations have been included for completeness.

The adequacy of a particular track system configuration with respect to safety can be assessed either by comparison of the estimated collision risk to a level of collision risk which has been previously determined to be acceptable, or by ranking according to magnitude the collision risks of all alternative configurations of the same track system. The latter comparison was used in this study.

ECONOMIC BENEFITS METHODOLOGY. The economic benefits methodology has as its objective the calculation of user cost savings resulting from the introduction of composite separation into the CEP. Fuel consumption and route transit time for CEP aircraft were initially taken as the two sources of user cost to be investigated. During the cost benefit analysis study, discussions with commercial and military users of the CEP revealed that reductions in track system transit time were considered to be of secondary importance. As a result, the economic benefits analysis concentrated on estimating fuel consumption for the various proposed CEP track system configurations.

A computer simulation program was developed in order to compare costs for the existing and proposed composite systems. The program, a discrete event model, simulated a day's track system activity. It accepted aircraft demanding service on a first-come, first-serve basis, assigned the aircraft to the most cost advantageous route and flight level available, and then moved the aircraft through the track structure being simulated. Simulation program outputs consisted of statistics concerning fuel consumption as well as comparisons of desired versus obtained routes and flight levels, and route transit times for the day. At certain locations in the simulated track system, the program tabulated information concerning the proximity of aircraft pairs for use in the collision risk analysis of proposed composite structures.

The distributions of aircraft demanding service from a simulated track system were based upon processing of the ATC facility data gathered during the data collection. The distributions reflected, for different seasons of the year, the types and origin/destination pairs of CEP aircraft on an hourly basis during a day. The preferred routes and flight levels, and the associated fuel consumption, and transit times were those obtained in the collection of flight planning data from CEP users.

The various track system configurations were simulated for different seasons of the year and average daily traffic counts. The resulting fuel consumption figures for each track system configuration were then assembled and compared on a relative basis in order to determine the most advantageous structure.

RESULTS OF COLLISION RISK ANALYSIS.

The estimates of lateral collision risk for the existing CEP track system and proposed CEP composite system B are presented in table 1 as a function of average daily traffic count. Also presented in table 1 is the estimated risk of collision due to the loss of planned composite separation in system B. The average number of daily flights observed during the data collection varied within the range 90 to 95, depending upon the season of the year. One hundred and thirty aircraft per day approximates the maximum daily traffic count observed from December 30, 1973, to June 30, 1974.

TABLE 1. COMPARISON OF ESTIMATED COLLISION RISK FOR EXISTING CEP TRACK SYSTEM AND PROPOSED COMPOSITE SYSTEM B

Average Daily Traffic Count	Expected Number of Accidents in 10 Million Track System Flying Hours due to Loss of Planned Lateral Separation		Expected Number of Accidents in 10 Million Track System Flying Hours due to Loss of Planned Composite Separation in System B
	Existing System	Proposed System B	
80	0.261	0.081	0.0025
90	0.314	0.090	0.0026
100	0.366	0.100	0.0026
130	0.525	0.127	0.0028
184 (1985 Estimate)	0.814	0.176	0.0031

The lateral collision risk model parameters describing navigation performance used in the calculations for the existing and proposed composite system were derived from the results of the 1973-1974 data collection. Thus, it was assumed that navigation performance would not change if the CEP track structure were changed in the manner of system B. The lateral collision risk model parameter describing the lateral proximity of aircraft pairs was estimated for the existing system from ATC facility data obtained during the data collection, and for proposed composite system B from the results of simulation.

The reduced lateral collision risk of system B in comparison to the existing structure can be attributed to two factors. First, the planned lateral separation between coaltitude traffic on adjacent routes in system B is nowhere less than that in the existing system and, in most areas, substantially larger. Second, for a given number of daily flights, the distribution of traffic among the six tracks of the proposed composite system gives rise to fewer laterally proximate pairs of aircraft than does the four track existing structure. From table 1 it is evident that the risk of collision due to the loss of planned composite separation in proposed system B is negligible in comparison to the lateral collision risk. This result pertains principally because the composite collision risk model assumes that the loss of all planned lateral separation is independent of the loss of all planned vertical separation. This assumption has been carefully considered by experts in the forum of the NAT/SPG and accepted as valid (reference 4).

RESULTS OF ECONOMIC BENEFITS ANALYSIS.

Table 2 presents the expected annual fuel and dollar fuel and dollar savings relative to the existing system which would result from the introduction of proposed composite system B. The savings are shown as a function of percent

increase of traffic over the daily average observed during the 1973-1974 data collection. The per gallon fuel costs shown in the table are the prices charged during late 1974 (30¢/gallon) and the 1974-projected price for 1976-1977 (44¢/gallon).

TABLE 2. ECONOMIC ADVANTAGE OF PROPOSED COMPOSITE SYSTEM B OVER EXISTING CEP TRACK SYSTEM

Percent of 1973-1974 Data Collection Average Daily Traffic Count	Annual Fuel Savings (1,000 lbs)	Annual Dollar Savings @30.0¢/Gal. ($1,000)	Annual Dollar Savings @44.0¢/Gal. ($1,000)
100	30,239	1,340	1,965
110	32,722	1,450	2,125
120	36,004	1,595	2,340
130	39,235	1,740	2,550
196 (1985 est.)	75,035	3,325	4,890

Figure 6 compares the expected annual cost savings relative to the existing system for system A and system B. The figure highlights the greater-than-linear savings achieved with either proposed composite structure as a function of increase in the percentage of average daily traffic.

CONCLUSIONS AND RECOMMENDATIONS

The estimated lateral collision risk for proposed composite system B is substantially lower than that for the existing CEP track system. In addition, proposed composite system B offers to CEP users the potential of significant fuel savings relative to the existing system. Hence, it is recommended that proposed composite system B be implemented on a trial basis in the CEP. It is further recommended that a monitoring program designed to assess the safety and operational impact of proposed composite system B be simultaneously initiated in the CEP.

COLLISION RISK AND ECONOMIC BENEFITS METHODOLOGIES

The feasibility of implementing composite separation in the CEP was based upon a comparison of the existing and any proposed composite track system with respect to the dual criteria of safety and cost. The methodological approaches for determining collision risk and cost are the subjects of this section. As a by-product to the exposition of the methodologies, the types and sources of data needed in order to compute collision risk and cost are also presented.

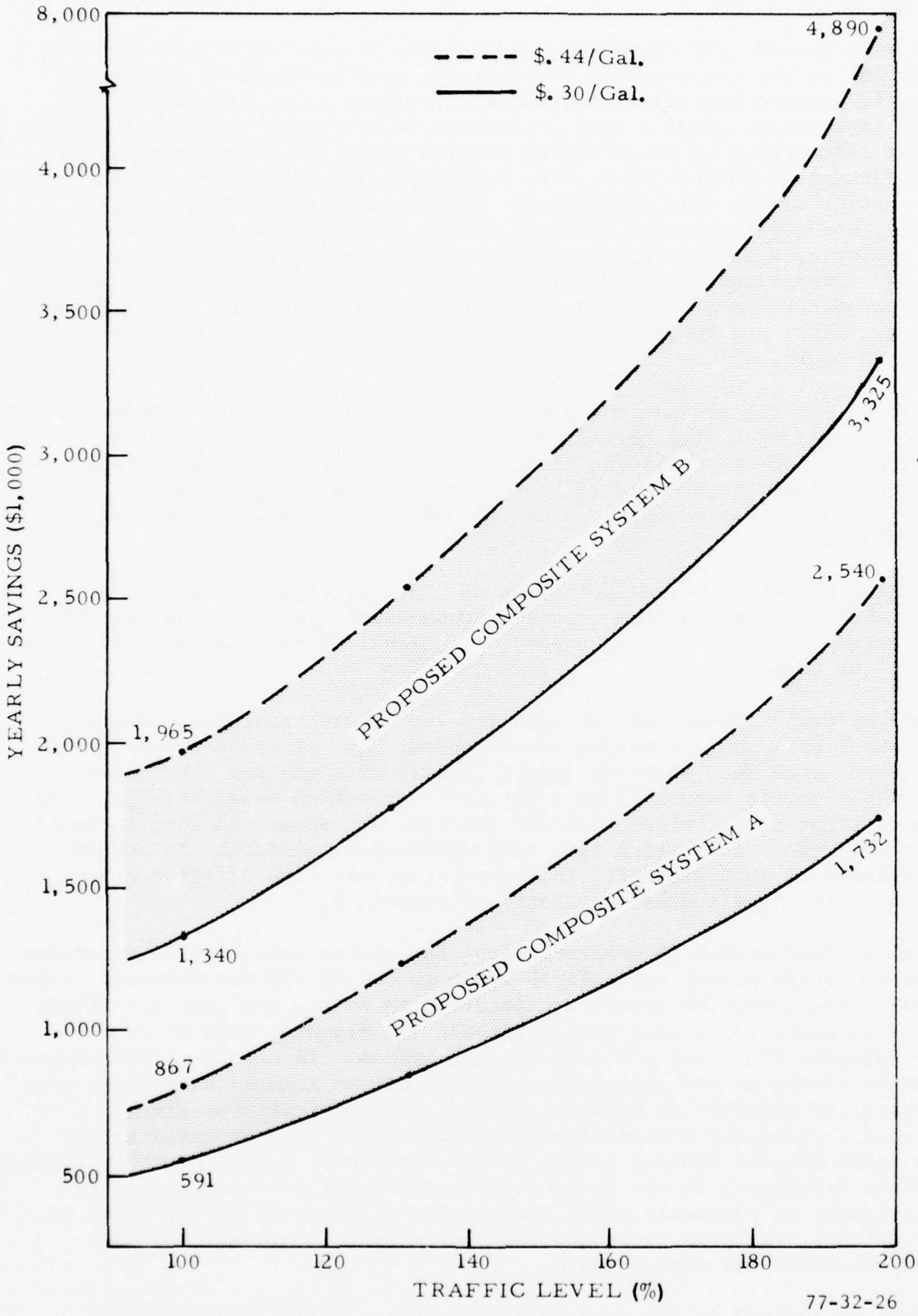


FIGURE 6. COST ADVANTAGE OF PROPOSED COMPOSITE TRACK SYSTEMS

COLLISION RISK METHODOLOGY.

Collision risk methodology consists of four basic steps. First, an abstract representation of the track system structure is made in terms of separation standards, or planned lateral, longitudinal, vertical (and, if applicable, composite) separation. Next a data collection is performed in order to obtain information descriptive of track system traffic flows and user aircraft navigation performance. In the third step, safety-related parameters are estimated from the results of the data collection. Finally, the end product of the methodology, the collision risk for each of the four planned separations, is computed employing a general mathematical model which has a different functional form for each dimension. The model relates the structure descriptive data and estimated parameters to a numerical value of collision risk, or expected number of midair accidents due to the loss of planned separation in 10 million track system flying hours.

As a result of several assumptions made in the derivation of the mathematical model of collision risk, the collision risk for each planned separation is shown to be independent of the collision risk for all other planned separations. Thus, the collision risk assignable to the track system under study is computed as the sum of the estimated longitudinal, lateral, vertical, and composite collision risks.

TRACK SYSTEM GEOMETRY. In the derivation of the collision risk model, it is assumed that the track system consists of parallel tracks or routes. The track system may be either of two types conventional (sometimes referred to as rectangular) or composite.

In the conventional system, any two adjacent routes are separated laterally from each other by a lateral separation standard, S_y. Aircraft on any given route are segregated into discrete flight levels, with any two vertically adjacent flight levels separated by a vertical separation standard, S_z. Same-route, same-flight-level, same-direction aircraft are separated longitudinally upon entry into the track system by a time difference sufficient to ensure safety. Translated into distance, this inter-aircraft time difference is referred to as the longitudinal separation standard, S_x.

The composite track system is generated from the conventional by the insertion of additional routes midway laterally between routes of the conventional system. The routes of the composite system are inserted in such a way that any flight level of a composite route lies midway between the flight levels of the laterally adjacent routes of the conventional system. In essence, the composite system may be viewed as two rectangular systems offset from each other by one-half a separation standard in both the lateral and vertical dimensions. Figures 1 and 2 presented a frontal view comparison of the conventional and composite track systems assumed in the model. As can be seen from these figures, each possible flightpath in the conventional system has two lateral and two vertical neighbor or proximate paths (neglecting flightpaths on the edges of the track system), while in the composite system, any flightpath has four additional diagonally proximate paths.

Any aircraft is assumed to fly on only one route and flight level while transiting the track system. Thus, traffic movement in the system is viewed as streams of aircraft on parallel routes and the average flow of aircraft per

unit time at any point in the structure is assumed constant and the same for all flight levels. Hence, it is possible to consider the exposure of a "typical" track system aircraft to the risk of collision.

Aircraft in the track system are assumed to be kept apart by imposition of the separation standards. No allowance is made for a reduction in collision hazard resulting from the surveillance of aircraft positions by ATC. Thus, the control assumed to be imposed upon the system is strategic or procedural in the strictest sense. In collision risk methodology, separation standards are looked upon as the control parameters which ATC manipulates to ensure safety. It should be noted that in actual practice CEP air traffic controllers do monitor the relative longitudinal positions of aircraft on the same route and flight level via position reports received from the aircraft at required longitudinal reporting points. If such reports indicate significant loss of along-track spacing, ATC imposes speed changes to regain longitudinal separation. Thus, the assumption of a purely strategic control philosophy in the track system leads to a conservative, or high, estimate of longitudinal collision risk.

<u>COLLISION RISK MODEL ASSUMPTIONS</u>. Under the parallel track system geometry described above, a midair collision between two aircraft can occur only as the result of errors made in flight planning or flying. The assumptions concerning these errors and other factors which influence collision risk are now presented.

An aircraft pair is said to be proximate if the two planned flightpaths bring the intended positions of the aircraft close to one separation standard in one dimension, while the planned separation is no larger than one separation standard in the other dimensions. With this definition in mind, the following collision risk model assumptions may now be stated:

(1) Potential collisions may occur only between proximate aircraft, and only two aircraft are involved in any one collision.

(2) There is no risk of collision between two aircraft with along-track, lateral, or vertical planned separation greater than one separation standard.

(3) The flying errors of an aircraft in the longitudinal, lateral, and vertical dimensions are assumed to be independent of each other.

(4) The flying errors of proximate aircraft are assumed to be independent of each other.

(5) A collision does not prevent the aircraft involved from completing the remainder of their flights.

(6) A typical track system aircraft is modeled as a slab of dimensions equal to the aircraft's metallic wingspan, length and height, and the slab is oriented with zero-degree bank, pitch, and yaw angles with respect to track.

(7) The collision risks for planned longitudinal, lateral, vertical, and composite separations are independent of each other.

(8) In clearing aircraft on flightpaths, ATC commits no errors which would make a midair collision a highly probable event (such as clearing two aircraft on the same route and flight level in opposite directions). This assumption is sometimes referred to as: "no ATC loop errors."

(9) No collision avoidance maneuvers are initiated as the result of visual or instrument (for example, weather radar) contact between aircraft.

(10) The navigation performance of an aircraft in the track system is the same in all parts of the track system and not a function of flight time or distance along track.

(11) All track system aircraft are of the same size and fly at the same speed.

Assumption 3 may be considered to be conservative, in the sense that it leads to a higher estimate of collision risk, since there are factors such as weather and external navigation aids which would tend to make the flying errors of proximate aircraft positively correlated. Assumption 8 may also be considered to be conservative. From assumption 2 the independence of errors in the horizontal and vertical planes follows. As is pointed out in reference 4, this assumption of independence of longitudinal-lateral and vertical errors is critical to the derivation of the collision risk model in the composite dimension.

Assumptions 3, 4, 5, and 6 when taken together make tractable the mathematically difficult task of deriving the collision risk model. From assumption 7, the overall collision risk may be computed as the sum of the longitudinal, lateral, vertical, and composite collision risks. The mathematical details of the derivation of the collision risk model may be found in appendix A.

<u>COLLISION RISK ESTIMATION EQUATIONS</u>. The expressions for collision risk associated with each of the four planned separations as derived in appendix A, are presented in and discussed in this section. These mathematical relationships make explicit the functional dependence of the risk of midair collision due to loss of planned separation upon parameters characterizing aircraft shape, track system separation standards, aircraft navigational performance, and system traffic density.

A concept central to the understanding of the mathematical relationships which follow is that of overlap of an aircraft pair. An aircraft pair, initially separated by a distance, L, in the r^{th} dimension (where r can be x, y, z) is said to overlap in the r^{th} dimension if the separation between the pair in the r^{th} dimension becomes less than λ_r. The initial separation may be a separation standard, half a separation standard, or zero nautical miles depending upon the separation planned between the two aircraft in dimension r. For example, two aircraft flying on adjacent routes have a planned lateral separation, L, of S_y; two aircraft flying on composite routes have a planned lateral separation, L, of zero nautical miles. Overlap can only occur because of flying errors.

The expressions for collision risk do not contain explicit terms describing the time during which aircraft pairs are proximate. Rather, a dimensionless term, called "occupancy," is employed in order to describe the exposure to possible collision. An aircraft pair is said to be proximate in dimension r (where r can be x, y, z, or yz - the composite or diagonal dimension) if the planned separation between the pair is one separation standard in dimension r and no greater than one separation standard in the remaining dimensions. Occupancy may then be defined as the ratio:

$$2 \times \frac{\text{(Average time during which pair is proximate in dimension r)}}{\text{(Average time during which pair can be proximate in dimension r)}}$$

The 2 arises since occupancy measures exposure to accidents of which there are two for a midair collision. The ratio may be expressed in terms of symbology as:

$$\text{occupancy} = 2x\ T_r/h$$

Where the subscript r has been appended to the time in order to indicate the restriction of the definition to dimension r.

Lateral Collision Risk Estimation Equation. Two aircraft assigned to the same flight level on laterally adjacent routes are exposed to the risk of lateral collision. The expression for N_{ay}, the expected number of accidents in 10 million track system flying hours due to the loss of all planned lateral separation, is:

$$N_{ay} = 10^7\, P_y(S_y)\, P_z(0)\, \frac{\lambda_x}{S_x} \left\{ E_y(\text{same}) \left[\frac{|\overline{\Delta V}|}{2\lambda_x} + \frac{|\overline{\dot{y}(S_y)}|}{2\lambda_y} + \frac{|\overline{\dot{z}(0)}|}{2\lambda_z} \right] + E_y(\text{opp}) \left[\frac{|\overline{V}|}{\lambda_x} + \frac{|\overline{\dot{y}(S_y)}|}{2\lambda_y} + \frac{|\overline{\dot{z}(0)}|}{2\lambda_z} \right] \right\} \quad (1)$$

Equation 1 demonstrates the functional dependence of the lateral collision risk, N_{ay}, upon parameters descriptive of aircraft size, separation standards, navigational performance, and traffic density.

Numerical values for the various parameters on the right side of equation 1 are obtained in diverse ways. The methods of obtaining these values shed light upon the sensitivity of N_{ay} to the different terms in the equation and provide insight into and rationale for the collision risk methodology.

With respect to the method of assigning specific numerical values, the parameters of equation 1 divide themselves into three classes; statutory, concurred, and estimated.

The statutory parameters are those which regulate the procedures for use of the track system; namely, the separation standards S_x, S_y, and S_z. By their nature, the separation standards are deterministic numbers and assume unique values in consort with the idealization of the actual track system as a parallel route structure in the first step of the collision risk methodology.

The concurred parameters are those which serve to typify the users of the actual track system. The intent of the concurred parameters is that the myriad of aircraft types and performance capabilities be replaced by a single aircraft model, the characteristics of which can be generally agreed to adequately represent in the idealized track system the range of physical characteristics found in the actual. Thus, in the risk model, all aircraft are idealized as a slab of dimensions equal to the concurred parameters λx, λy, and λz. Likewise, the representative aircraft in the idealized system has its speed represented by the concurred parameter $\overline{V}$. As can be appreciated intuitively from consideration of the slab, the larger the values of the concurred parameters, the larger is the estimated lateral collision risk. In fact, the collision risk methodology models the typical aircraft in the idealized track system as the largest, fastest aircraft in the actual track system.

Because of the paucity of data descriptive of the altitude-maintaining capability of aircraft, particularly in an oceanic environment, a second area in which concurred parameters figure prominently is in the modeling of vertical position-keeping. Thus, the NAT/SPG concurred with values for $P_z(0)$ and $|\dot{z}(0)|$, based upon considerations of theoretical aspects of aircraft vertical position-keeping systems and published data. Facing the same problems for a similar system, CEP collision risk estimates in all dimensions are computed using the NAT/SPG concurred values of the vertical position-keeping parameters.

The estimated parameters are those which characterize navigation performance and traffic density. As the name implies, estimated parameters assume values based upon observational data taken in the actual track system under study. Unlike the statutory and concurred parameters, estimated parmeters are stochastic in nature. That is, estimated parameters are described by a distribution of possible values with the most typical or central estimate of the parameter taken as the mean of the distribution. In equation 1, the estimated parameters are the probability of lateral overlap, $P_y(S_y)$, the relative along and crosstrack velocities, $|\Delta \overline{V}|$ and $|\dot{y}(S_y)|$, and the same and opposite direction lateral occupancies, E_y(same) and E_y(opp).

Gathering data and characterizing the estimated parameters constitutes the third step of the collision risk methodology. It should be clear that two actual oceanic track systems, both conceptualized as parallel track systems with identical separation standards and concurred parameters, will differ with respect to estimated collision risk insofar as aircraft navigational performance and traffic density, as reflected by the estimated parameters, differ between the two systems.

Sensitivity of N_{ay} to lateral collision risk model parameters. The sensitivity of N_{ay} to the various terms on the right side of equation 1 has been investigated by the NAT/SPG and others (references 5 and 6). For a given conceptualized parallel track system and representative aircraft, N_{ay} will vary as the estimated parameters are varied. It has been found that N_{ay} is most sensitive to the probability of lateral overlap, $P_y(S_y)$. In turn, since $P_y(S_y)$ is determined from the self convolution of the distribution of lateral deviations, f(Y), via:

$$P_y(S_y) = 2\lambda_y \int_{-\infty}^{\infty} f(Y)\ f(S_y + Y)\ dY$$

N_{ay} is sensitive to the distributional form of f(Y). Defining the tail region of f(Y) to be that portion of the distribution of observed lateral deviations at least as large in magnitude as $S_y/2$ from course, investigation has shown that $P_y(S_y)$, and hence N_{ay}, is most sensitive to both the shape and area of the tail region of f(Y).

As is indicated in reference 6, the estimation of the shape of the tail region of f(Y) is difficult, since relatively few observations of lateral deviations from course at least as large in magnitude as $S_y/2$ will arise during a track system data collection. As a result, the shape of the tail region is modeled in a conservative manner, in the sense that the shape chosen will result in a large value of $P_y(S_y)$ relative to values which would arise for choices of other shapes.

Given the conservative compromise with respect to tail region shape, $P_y(S_y)$, and hence N_{ay}, can thus be seen to be most sensitive to the frequency of observed lateral deviations at least as large in magnitude as $S_y/2$ from course. Hence, in any track system data collection designed to characterize the estimated parameters of the lateral collision risk model, heavy emphasis must be placed upon ensuring that the frequency of large lateral flying errors be accurately recorded. The analysis of large errors observed during the CEP data collection is presented in appendix B.

After $P_y(S_y)$, N_{ay} is most sensitive to the same- and opposite-direction lateral occupancies which describe the proportion of aircraft exposed to the risk of lateral collision. Analysis indicates that N_{ay} is relatively less sensitive to the remaining estimated parameters. Details concerning the estimation of Ey(same) and Ey(opp) are presented in appendix A.

The sensitivity of N_{ay} to the various estimated parameters is presented under the assumption that the conceptualized parallel track system is fixed, that is, that the statutory and concurred parameters are held constant. The process of investigating modifications to or alternative configurations of an existing track system frequently involves conceptualizing alternate parallel track systems with concommitant changes in separation standards. In particular, operational considerations relative to increasing system capacity may dictate investigation of structures with a lateral separation standard reduced from that of the existent system. It is important to note that, with regard to statutory parameters, N_{ay} is quite sensitive to any change in S_y. This sensitivity exists because any modification of the value of S_y perforce, for a given set of observed lateral deviations, redefines the tail region of f(Y) and hence almost certainly increases or decreases the frequency of large lateral flying errors.

Composite Collision Risk Estimation Equation. Two aircraft assigned to flight levels within $S_z/2$ of each other on diagonally adjacent routes are exposed to risk of collision because of the loss of all planned composite separation. The expression for N_{ayz}, the expected number of accidents in 10 million track system flying hours due to the loss of all planned composite separation, is:

$$N_{ayz} = 10^7 P_y\left(\frac{S_y}{2}\right) P_z\left(\frac{S_z}{2}\right) \frac{\lambda_x}{S_x} \left\{ E_{yz}\ (\text{same}) \left[\frac{\overline{|\Delta V|}}{2\lambda_x} + \frac{\overline{|\dot{y}\ (S_y/2)|}}{2\lambda_y} + \frac{\overline{|\dot{z}\ (S_z/2)|}}{2\lambda_z} \right.\right.$$

$$\left.\left. + E_{yz}\ (\text{opp}) \left[\frac{\overline{V}}{\lambda_x} + \frac{\overline{|\overline{\dot{y}}\ (S_y/2)|}}{2\lambda_y} + \frac{\overline{|\dot{z}\ (S_z/2)|}}{2\lambda_z} \right] \right\} \quad (2)$$

N_{ayz} is also functionally dependent upon statutory, concurred, and estimated parameters. As in the lateral collision risk model case, the statutory parameters are the track system separation standards S_x, S_y, and S_z with the associated composite standards $S_y/2$. The concurred parameters are λx, λy, λz, P_z $(S_z/2)$, and $\overline{|\dot{z}\ (S_z/2)|}$, where, because of the inability to obtain track system data adequate to model vertical position-keeping, the Fifth Meeting of the NAT/SPG (reference 7) concurred upon a method for estimating $P_z(S_z/2)$. Finally, the estimated parameters of the composite collision risk model are $P_y(S_y/2)$, $E_{yz}(\text{opp})$, $E_{Ey}z(\text{same})$, $\overline{|\dot{y}(S_y/2)|}$, and $\overline{|\Delta V|}$.

Of particular note in equation 2 is the product of the terms describing the losses of all planned lateral and vertical separation, $P_y(S_y/2)\ P_z(S_z/2)$. Noting the obvious similarity of terms in equations 1 and 2, it might be expected that the probability of losing all planned composite separation between an aircraft pair would appear as $P_{yz}(S_y/2,\ S_z/2)$. However, because lateral and vertical flying errors are assumed to be independent, then:

$$P_{yz}(S_y/2,\ S_z/2) = P_y(S_y/2)\ P_z(S_z/2)$$

This result is critical to the estimated value of N_{ayz}, for if there is positive correlation between lateral and vertical flying errors, a value of composite collision risk higher than that which would result from equation 2 applies.

Sensitivity of N_{ayz} to composite collision risk model parameters. For fixed values of the statutory and concurred parameters, N_{ayz} is found to be most sensitive to the probability of lateral overlap, $P_y(S_y/2)$. Unlike the lateral collision risk case, however, $P_y(S_y/2)$ is not sensitive to the tail region of the observed distribution of track system lateral deviations. Rather, since $P_y(S_y/2)$ (the probability that an aircraft pair with planned lateral separation $S_y/2$ will lose all planned lateral separation) is determined from the self convolution of $f(Y)$ by:

$$P_y(S_y/2) = 2\lambda_y \int_{-\infty}^{\infty} f(Y)\ f(Y + S_y/2)\ dY,$$

The shape and area of the core of the distribution f(Y) will determine the value of $P_y(S_y/2)$. It can be shown (appendix A) that if lateral course-keeping ability improves, as evidenced by a decreasing standard deviation of the core of f(Y), the composite collision risk decreases.

The sensitivity of N_{ayz} to the remaining estimated parameters is similar to that of N_{ay}. The same and opposite-direction composite occupancies have the most impact upon N_{ayz}, followed by $\overline{|\dot{y}\ (S_y/2)|}$ and $\overline{|\Delta V|}$.

Vertical collision risk estimation equation. Two aircraft assigned to the same route at adjacent flight levels are exposed to the risk of collision because of the loss of all planned vertical separation. The expression for N_{az}, the expected number of accidents in 10 million track system flying hours due to the loss of all planned vertical separation, is:

$$N_{az} = 10^7 \, P_y(0) \, P_z(S_z) \, \frac{x}{S_x} \, E_z(\text{same}) \left[\frac{\overline{|\Delta V|}}{2\lambda_x} + \frac{\overline{|\dot{y}\ (0)|}}{2\lambda_y} + \frac{\overline{|\dot{z}\ (S_z)|}}{2\lambda_z} \right] + E_z(\text{opp}) \left[\frac{\overline{|V|}}{\lambda_x} + \frac{\overline{|\dot{y}\ (0)|}}{2\lambda_y} + \frac{\overline{|\dot{z}\ (S_z)|}}{2\lambda_z} \right] \quad (3)$$

Because of the previously mentioned difficulty with properly estimating vertical position-keeping parameters, particularly $P_z(S_z)$, the NAT/SPG at their Fifth Meeting (reference 7) concurred on a value of N_{az}. Confronted with the same difficulties as was the NAT/SPG, the value of N_{az} for the CEP was taken as the same as that for the North Atlantic track system, with a modification which will be discussed in the section on CEP collision risk estimates.

Longitudinal Collision Risk Estimation Equation. Two sequential aircraft assigned to the same route at the same flight level in the same direction are exposed to the risk of collision because of the loss of all planned longitudinal separation. Because of the nature of a parallel track system, two aircraft at the same flight level on adjacent routes have a unique planned lateral separation, S_y. Similarly, two aircraft on the same route at adjacent altitudes have a unique planned vertical separation, S_z. However, the planned separation between two aircraft at the same altitude on the same route is not a unique value. Rather, since aircraft may enter a track system at some rate which is below that required to saturate the available airspace, the resulting planned longitudinal separation between a same-route, same-flight-level, same-direction aircraft pair may be any distance at least as large as the minimum longitudinal separation standard, S_x. Operationally, controllers assign time, rather than distance, separations between two aircraft on the same route at the same altitude. Since the time intervals between aircraft are assigned in integral numbers of minutes, in practice a large number of planned discrete time separations at least as large as the minimum time separation corresponding to S_x (plus an allowance for mach number difference between aircraft) are possible.

Within the constraint of a minimum time separation corresponding to S_x, the planned separation between two aircraft is a random variable, since the arrival of aircraft at the entry gateways of a track system is a random event. As a result of the randomness of planned separations, the longitudinal overlap probability πx, is computed in a manner different from that employed in the lateral case. Defining $E_x(t)$ as the probability that a pair of aircraft have an initial longitudinal separation of exactly t minutes after correction for mach number differences and $P_x(t)$ as the probability that a pair of aircraft lose exactly t minutes initial longitudinal separation after correction for mach number differences,

$$\pi x = \frac{4\ \lambda_x}{\bar{V}/60} \quad \sum_t E_x(t) P_x(t)$$

where the summation extends over all possible planned separations, t. The expression for N_{ax}, the expected number of accidents in 10 million track system flying hours due to the loss of all planned longitudinal separation, is:

$$N_{ax} = 2 \times 10^7 \left[\frac{|\overline{V}|}{2\lambda_x} + \frac{|\overline{\dot{y}(0)}|}{2\lambda_y} + \frac{|\overline{\dot{z}(0)}|}{2\lambda_z} \right] P_y(0)\ P_z(0)\ \pi_x \qquad (4)$$

N_{ax} can be seen to be functionally dependent upon statutory parameters (planned longitudinal separations, t), concurred parameters(λ_x, λ_y, λ_z, $P_z(0)$, $|\overline{\dot{z}(0)}|$), and estimated parameters ($P_x(t)$, $E_x(t)$, $P_y(0)$, $|\overline{\Delta V}|$, $|\overline{\dot{y}(0)}|$).

<u>Sensitivity of N_{ax} to longitudinal collision risk model parameters</u>. Because of the multiplicity of possible planned separations for along-track aircraft pairs, it is not possible to consider the sensitivity of N_{ax} to estimated parameters with statutory parameters held fixed. N_{ax} is sensitive to the probability of longitudinal overlap π_x. Thus, if the along-track position-keeping ability of aircraft improves (as reflected in smaller values of $P_x(t)$ for t at least as large the minimum longitudinal separation) and all other factors remain static, N_{ax} decreases. Conversely, if the track system becomes more densely packed (as reflected in higher values of $E_x(t)$ for t near the minimum longitudinal separation), N_{ax} increases if other model parameters remain constant.

The longitudinal collision risk is also sensitive to $P_y(0)$, the probability that two in-trail aircraft maintain their zero planned lateral separation. The quantity $P_y(0)$ is determined from the self convolution of f(Y) via:

$$P_y(0) = 2\lambda_y \int_{-\infty}^{\infty} f^2(Y)\ dY$$

It can be shown that $P_y(0)$ is inversely proportional to the standard deviation, σ, of f(Y).

Since an overall improvement in lateral position keeping by track system aircraft will be mirrored in a reduction of σ, an apparent paradox arises. Under the collision risk model assumption of dimensional independence of flying errors, as the ability of track system aircraft to maintain small crosstrack

navigational errors improves, the longitudinal collision risk in the system increases. This apparent paradox can be explained by noting that as the majority of track system aircraft stay closer to track centerline, a grossly aberrant longitudinal navigator has an increased chance of coming into contact with someone.

ECONOMIC BENEFITS METHODOLOGY.

The economic benefits analysis of the CEP required a comparison of the system which is presently in use to hypothetical systems. Since actual measurements are unavailable for the hypothetical systems, the only practical means of comparison was through computer simulation. The basic approach was the construction of a computer simulation model of the CEP patterned after that developed by the NAT/SPG. The model was designed to provide outputs yielding a comparison of costs between the existing track system and the proposed alternative composite track systems and also to provide the necessary occupancy estimates for the collision risk analysis of the composite structures.

ECONOMIC BENEFITS SIMULATION MODEL ASSUMPTIONS. In order to keep the analysis tractable, the following assumptions were adopted:

(1) Aircraft reach cruise altitude at or prior to the gateway

(2) There are no route or altitude changes enroute

(3) Aircraft operate at constant speed between gateways

(4) Aircraft, with the exception of the KC135, fly at constant mach number; the KC135 operates at a constant true airspeed of 450 knots regardless of altitude.

These assumptions are similar to those of the NAT/SPG economic benefits analysis investigations.

SIMULATION PROGRAM OVERVIEW. The simulation program was written in the FORTRAN IV computer language and was developed principally to perform economic benefit analysis and to provide occupancy estimates for the collision risk analysis of the proposed alternative composite systems. It however, was structured so that it could be used for studies in which navigation and surveillance subsystems would be examined. Varying numbers of terminals, routes, altitudes, aircraft types, data collection points, and time intervals defining traffic density can be specified. Inputs to the model which provide this flexibility include:

(1) Number of flights and simulation replications,

(2) Number of terminals, routes, altitudes, aircraft types, and number of data collection points and locations,

(3) Daily traffic demand histogram, demand multipliers, and time interval size,

(4) Demand data cards by terminal, aircraft type, and time period,

(5) Route distances and path flying times by aircraft type,

(6) Route preferences and associated fuel burn and flight time by aircraft type,

(7) Longitudinal separation matrix, and

(8) Proximate pair calculation control cards.

The basic program flow and logic are shown in a high-level flow chart, appendix C. The program is an event model, with time kept in seconds and advanced at the completion of each event to the time of the next event. Events are stored chronologically in a table. Examples of events are the entry of an aircraft into the system, the periodic position update of a flight as it traverses the track system, and the exit of an aircraft from the structure. When an aircraft enters the system, a position update event associated with the aircraft is entered into the event table. When this event transpires, a second position update is scheduled. This process of linking the occurrences of position update events continues until an exit event for the flight is generated. Summary statistics for the aircraft are collected upon exit, and after an input-specified number of exit events (corresponding to the number of days to be simulated) have occurred, the simulation is terminated. Several facets of the simulation model are now discussed.

TRAFFIC GENERATION. In an initial phase of program execution, traffic mix tables and cumulative traffic density distributions are developed from input data. In order to characterize the day-to-day variation in traffic levels, a daily traffic volume scale factor is chosen by random number techniques from the daily traffic histogram compiled from the observed daily total traffic in the track system. Thus, during a single computer run, roughly the same proportion of busy and quiet days will occur as in the actual track system environment. The factor is then used to scale aircraft demand distributions which are formulated by type and time period when entry into the system is sought. Entry times for the specific number of each type of aircraft by time period are generated from a uniform distribution and sequenced by time. Using the above procedure, diurnal (i.e., day/night) traffic patterns are incorporated into the simulation model. By having traffic densities vary as a function of time, the realism of generating peak hour traffic is achieved. This is desirable because fuel penalties and occupancies are larger under peak conditions.

ROUTE ASSIGNMENT LOGIC. It is assumed that aircraft are assigned to tracks on a first-come-first-serve basis, and that each entrant is assigned to the most desirable route and flight level (or path) available for the aircraft type. A path is considered available at a given time if assignment of an entering aircraft to the path at that moment would not result in a longitudinal conflict with another aircraft at any later time in the track system. The choice of the most desirable path from among those which are available is based on the path preferences read in as input data. Generally, but not always, the preferences

are based on paths requiring the least fuel consumption. The modeling of path preferences for the KC135 differed from the procedure used for the other aircraft types because the Strategic Air Command (SAC) indicated that, due to the type of navigational equipment used, a change in requested flight level is always preferred to a change in route.

The longitudinal separation standard employed between aircraft is determined from input data. For simulations of the CEP, the separation standard used was 15 minutes flying time between aircraft. The initial longitudinal separation between aircraft in the vicinity of the departure-point gateway must be sufficient to assure that the 15-minute separation is maintained throughout the flight. Thus, if a slow aircraft is followed by a fast aircraft, greater initial separation is alotted to guarantee sufficient separation during the remainder of the flight. In this case, an additional 5 minutes per 0.02-mach-number difference is required.

Preliminary runs of 60 days traffic in the existing CEP track system were made to compare results obtained through simulation with that which actually occurred. In this process, it was found that the actual data exhibited greater variability than that predicted by the model.

Differences between the actual and simulated systems with respect to track assignment distributions were of particular concern, since the estimated magnitudes of horizontal and composite proximity are critically dependent upon these distributions. Therefore, a number of features were added to the path selection logic to achieve greater realism in modeling system diffuseness.

Route and flight level preferences for each CEP aircraft type predicted from flight planning data were compared to those actually chosen, as reflected in track system data. Differences between what was chosen and what ought to have been chosen were used to formulate a second set of preferred routes and flight levels for each aircraft type and to estimate the percentage of time such preferences were opted. The existing CEP was then resimulated, and entering aircraft were allocated preferred routes and flight levels such that nonoptimal choices were made inproportion to those observed in the actual data. The route and flight level preferences resulting from this process satisfactorily approximated those of the real system.

AIRCRAFT POSITION UPDATE. Aircraft positions are updated periodically by initiation of a position update event. An initial position update event is generated for an aircraft when it enters the simulation, and subsequent position update events are generated each time a position update event is activated. When an aircraft position is updated, a test is made to determine if the aircraft has crossed a data slice (position for recording information relative to the given flight). If so, the time of crossing is saved for future use in estimating occupancies for collision risk analysis.

The simulation model possesses several features which were not utilized in the present study, but which make it possible to perform studies involving surveillance accuracies and update rates. Provision for controlling navigation performance in the vertical, lateral, and longitudinal planes is made with the

capability of inputting data defining the navigation system characteristics. Inputs include such parameters as surveillance rate and accuracy; typical vertical, lateral and longitudinal navigation error rates; probabilities and magnitudes of navigational blunders in the vertical and lateral planes; fix position updating accuracy; and time distribution for fix position updates.

OCCUPANCY ESTIMATION. The procedure for allocating aircraft to paths determines the distribution of aircraft on the various paths leading to fuel burn and flying time estimates. In addition, this distribution of aircraft influences the lateral and composite collision risks, since risk is dependent upon the proximity of pairs of aircraft on adjacent paths, and the amount of proximity or occupancy for a given system depends upon the pattern of utilization of the paths. In order to assure that estimates of cost and risk for a track system are consistent with each other, the estimates for both quantities are based on a common set of traffic modeling assumptions. Therefore, the simulation model also monitors aircraft proximity. The simulation allows aircraft from both eastern and western terminals to be fed into the system simultaneously. This was done, since there is considerable overlap between eastbound and westbound daily traffic profiles in the CEP and thus, for alternative composite systems, it was necessary to estimate opposite-direction composite occupancy as well as same-direction lateral and composite occupancy.

For this study, five data slice planes were defined at positions in simulated systems where flight statistics were desired. Two were located nearby to the gateway entry points and a third was located at the midpoint of the CEP. For the existing CEP track system, simulated results at these data slices were compared with the historical data collected at the corresponding required reporting points in the actual system. Good agreement was found. Two additional data slices were defined midway between the gateway and the midpoint data slices. Figure 7 shows the locations of the data slices used for system A. When an aircraft position is updated, a determination is made as to whether the aircraft has passed through a data slice. If so, its time of crossing is calculated and saved for occupancy calculations.

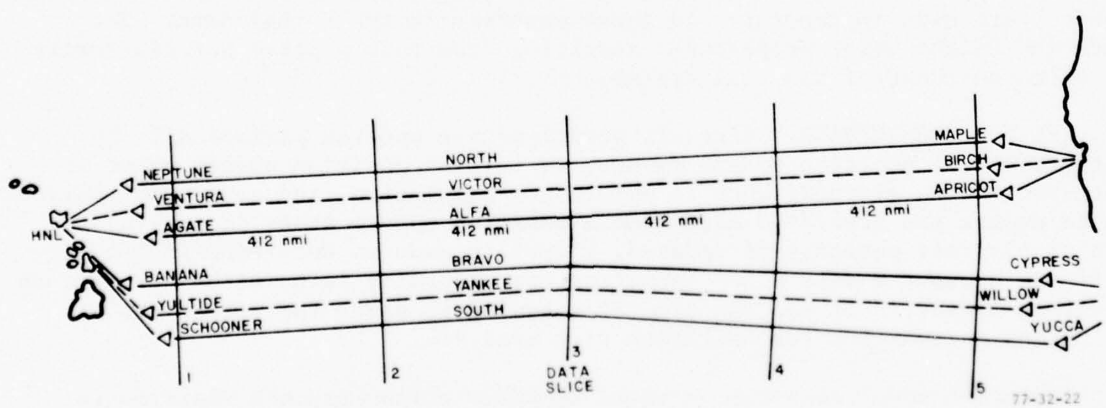


FIGURE 7. DATA SLICE POSITIONS USED IN SIMULATION OF PROPOSED ALTERNATIVE CEP COMPOSITE SYSTEM A

Opposite-direction proximate pairs are calculated by systematically scanning the tracks for those tracks which could present opposite-direction lateral or composite proximities. If either of two adjacent routes has zero aircraft, no proximity can occur, while if both show nonzero numbers of aircraft, the time and position of each passing is computed and compared to the data slice locations. The proximate pairs associated with the appropriate data slice and track are then tallied.

Same-direction proximate pairs are also calculated by using the data slice crossing times. As each aircraft passes through a data slice, the appropriate adjacent tracks are examined for crossing times which would reflect either same-direction lateral or composite proximity. For purposes of this simulation, same-direction lateral or composite proximity was defined as any pair of aircraft crossing a data slice within 15 minutes of each other. Longitudinal proximity was obtained from the data slice crossings times of aircraft on the same track.

COMPUTER PROGRAM OUTPUTS. The output of the simulation model is designed to provide the needed information and statistical summaries relative to the cost benefit analysis and occupancy information required in the collision risk analysis. Included in the output are: (1) route preference availability tables by aircraft type, which indicate the frequency with which aircraft were given the path of first or subsequent choices; (2) total number of flights, fuel burn and flying time from each terminal; (3) total number of flights, fuel burn and flying time for each type of aircraft; (4) same- and opposite-direction lateral and composite proximate pairs listed by route, flight level, direction of flight, and data slice; (5) grand totals of lateral and composite proximate pairs; and (6) interarrival times at the data slices by route and flight level which can be used in developing estimates of longitudinal occupancy.

DATA COLLECTION PROGRAM AND RESULTS

Certain parameters of the collision risk model and certain factors in the economic benefits analysis of route structures must be estimated from data taken in the track system under study. At the September 1973 Pacific Asia Regional Air Navigation Conference in Honolulu, the United States announced that it intended to study the feasibility, from both a collision risk and cost benefit standpoint, of implementing composite separation in the CEP. Simultaneously, the United States also announced that a data collection program would be undertaken in the CEP from December 15, 1973, to June 30, 1974, in order to obtain data adequate to estimate the required collision risk and cost parameters.

The types of data required were identified as: (1) radar position measurements, (2) ATC facility data, (3) CEP flight crew survey form, and (4) commercial and military flight planning data.

Distributions of lateral deviation from course and relative along-track and crosstrack velocity were to be extracted from the radar position measurements. The ATC facility data, consisting of flight progress information and ancillary data maintained by the FAA's Oakland and Honolulu ARTCC's were to be used to estimate occupancies for the collision risk model. Distributed to aircraft flying in the track system, the CEP flight crew survey form was to provide information on desired and obtained flight plans, and the performance of navigation equipment in transit. The commercial and military flight planning data detailed preferred flight plan and alternative strategies in terms of route and flight level to be followed by CEP user aircraft types. It was to form a key part of the data for simulations of alternative track system configurations.

The 6 1/2-month data collection program in the CEP was designed, insofar as possible, to obtain information of a quantity and quality comparable to that obtained in the North Atlantic organized track system during a similar exercise in 1967. However, the CEP track system configuration and environment required that certain modifications to NAT/SPG data collection procedures be adopted. The existing CEP track system is now discussed. Subsequent sections describe the data collection program, detail the information gathered and present risk model parameter estimates derived from the data.

EXISTING CEP TRACK SYSTEM DESCRIPTION.

The existing CEP track system is depicted in figure 3. The route system consists of northern and southern boundary routes, North and South, and central routes, Alfa and Bravo. The eastern and western termini, or gateways, of the routes are presented in table 3.

TABLE 3. CEP ROUTES AND GATEWAYS

Eastern Gateway	Route	Western Gateway
Maple	North	Neptune
Apricot	Alfa	Agate
Cypress	Bravo	Banana
Yucca	South	Schooner

The four routes are approximately parallel from the western gateways to longitude 140° West with lateral separation between adjacent routes of approximately 100 nmi. Eastward from 140° West to the eastern gateways, the northern two routes, North and Alfa, are reasonable parallel with lateral separation of about 100 nmi. Likewise, the southern two routes, Bravo and South, are nearly parallel, with lateral separation of approximately 110 nmi. However, these route-pairs diverge from 140° West eastward at about 9°.

The two northern routes are principally used to accommodate traffic between the San Francisco Bay area and Hawaii. In addition, most direct flights between points interior to the continental United States and Hawaii use North or Alfa. The southern two routes are generally used by traffic between the Los Angeles area and Hawaii.

Responsibility for control of air traffic is divided between the Oakland, California, and Honolulu, Hawaii, ARTCC oceanic sectors. An aircraft westbound on North or Alfa route proceeds under the positive radar control of an Oakland ARTCC domestic sector to a distance approximately 50 nmi west of the eastern gateways, at which time radar coverage ceases, and control responsibility passes to the Oakland Oceanic Sector. In a similar manner, an aircraft on Bravo or South route begins the oceanic crossing under the positive radar control of a Los Angeles ARTCC domestic sector and is handed over to the Oakland Oceanic Sector as radar surveillance ceases, some 40 to 50 nmi west of the eastern gateways. Control responsibility shifts to the Honolulu ARTCC Oceanic Sector as the flight passed 140° West. As the aircraft enters radar coverage in Hawaii, the Honolulu Oceanic Sector relinquishes control to a Honolulu ARTCC domestic sector at which time positive radar control of the aircraft is reestablished.

The traffic on any CEP route is segregated by flight level between FL290 and FL410, with a vertical separation standard of 2,000 feet between adjacent permissible flight levels. Traffic flow on a given flight level is unidirectional for all routes, the direction being a fixed constant of the system. That is to say, traffic is either eastbound or westbound on a given flight level for any route, regardless of the time of day or season of the year. Table 4 presents the usable flight levels and associated directions of flight for the existing CEP track system.

TABLE 4. CONSTANT DIRECTION ASSIGNMENT OF FLIGHT LEVELS IN EXISTING CEP (ALTITUDE = FLIGHT LEVEL X 100)

Flight Level	Direction	Flight Level	Direction
290	East	370	East
310	West	390	West
330	East	410	East
350	West		

EXISTING CEP SYSTEM ENVIRONMENT. The meteorological environment in the CEP track system is generally considered to pose considerably less severe problems to air navigation than does that in the North Atlantic. Pronounced seasonal climatic changes, severe turbulence, and strong winds aloft are not frequently observed in that portion of the Pacific Ocean area containing the route structure.

As in all oceanic track systems, aircraft navigation in the CEP is performed either by onboard self-contained systems, such as inertial navigation (INS) or a hybrid of Doppler-computer-celestial navigation, or by a combination of onboard systems updated by position fixes obtained from long-range navigation aids. Analysis of ATC facility data and CEP flight crew survey forms revealed that approximately 53 percent of the flights in the CEP track system during the data collection period employed INS as the method of navigation, while 2 to 3 percent made use of onboard hybrid systems. The remainder of the aircraft relied upon systems containing mixtures of onboard and long-range navigation aids for guidance.

One type of long-range navigation aid available in the CEP is a group of LORAN A chains on both the west coast of the continental United States and the Hawaiian Islands. These LORAN A chains serve the civilian users of the track system and the coverage provided is generally regarded as good, with some degradation of quality in reception apparent in the middle of the track system. Military users of the CEP have available an Hawaiian LORAN C chain which provides coverage from the western gateways of the track system to 140° West. From 140° West to the route system's eastern gateways, military users must rely on a CONSOLAN System which is of limited range and accuracy relative to LORAN A.

EXISTING CEP SYSTEM UTILIZATION. During the period December 15, 1973, to June 30, 1974, ATC facility data yielded information on 18,570 flights in the CEP. In order to understand the mechanics of CEP utilization, these data were culled to produce statistics concerning route utilization and systems users.

Existing CEP Route Utilization. Table 5 presents the summary statistics of route utilization during the data collection period. The total number of 17, 860 aircraft in the table are those which flew on only one CEP route while traversing the system. A total of 558 aircraft used more than one route (such as Agate to 140° West on Alfa and 140° West to Cypress on Bravo) during oceanic flight. In addition to this cross-route traffic, 152 aircraft flew either slightly north or south of the organized track system during the crossing between Hawaii and either the Los Angeles or San Francisco areas.

TABLE 5. ROUTE UTILIZATION BY DIRECTION AND TOTAL, DECEMBER 15, 1973, TO JUNE 30, 1974

	Eastbound		Westbound		Total	
Route	Count	Percent of Eastbound	Count	Percent of Westbound	Count	Percent of Total
North	478	5.7	671	7.1	1,149	6.4
Alfa	3,633	43.0	4,349	46.1	7,982	44.7
Bravo	3,616	42.9	3,610	38.3	7,226	40.5
South	708	8.4	795	8.5	1,503	8.4
Total	8,435	100.0	9,425	100.0	17,860	100.0

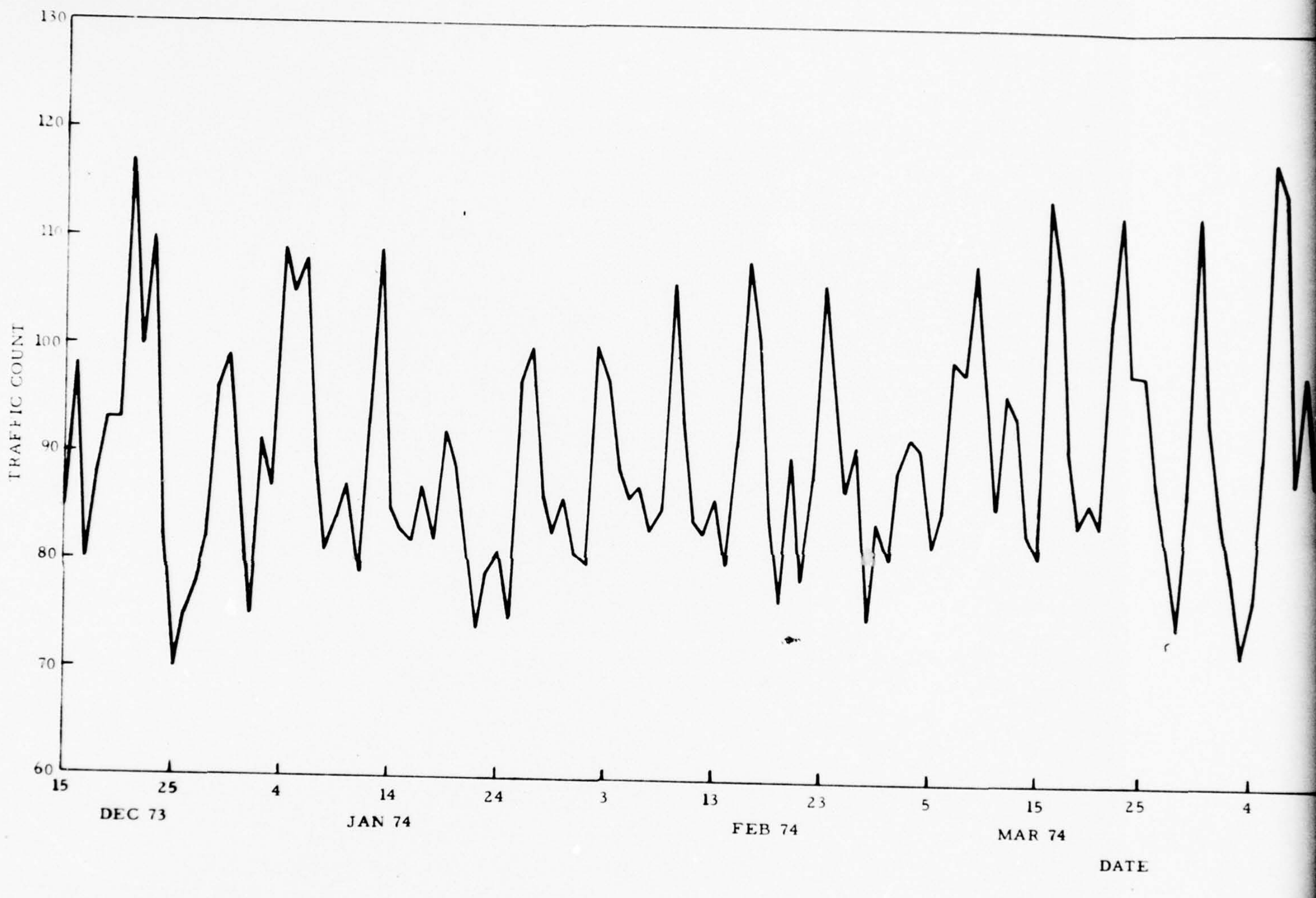
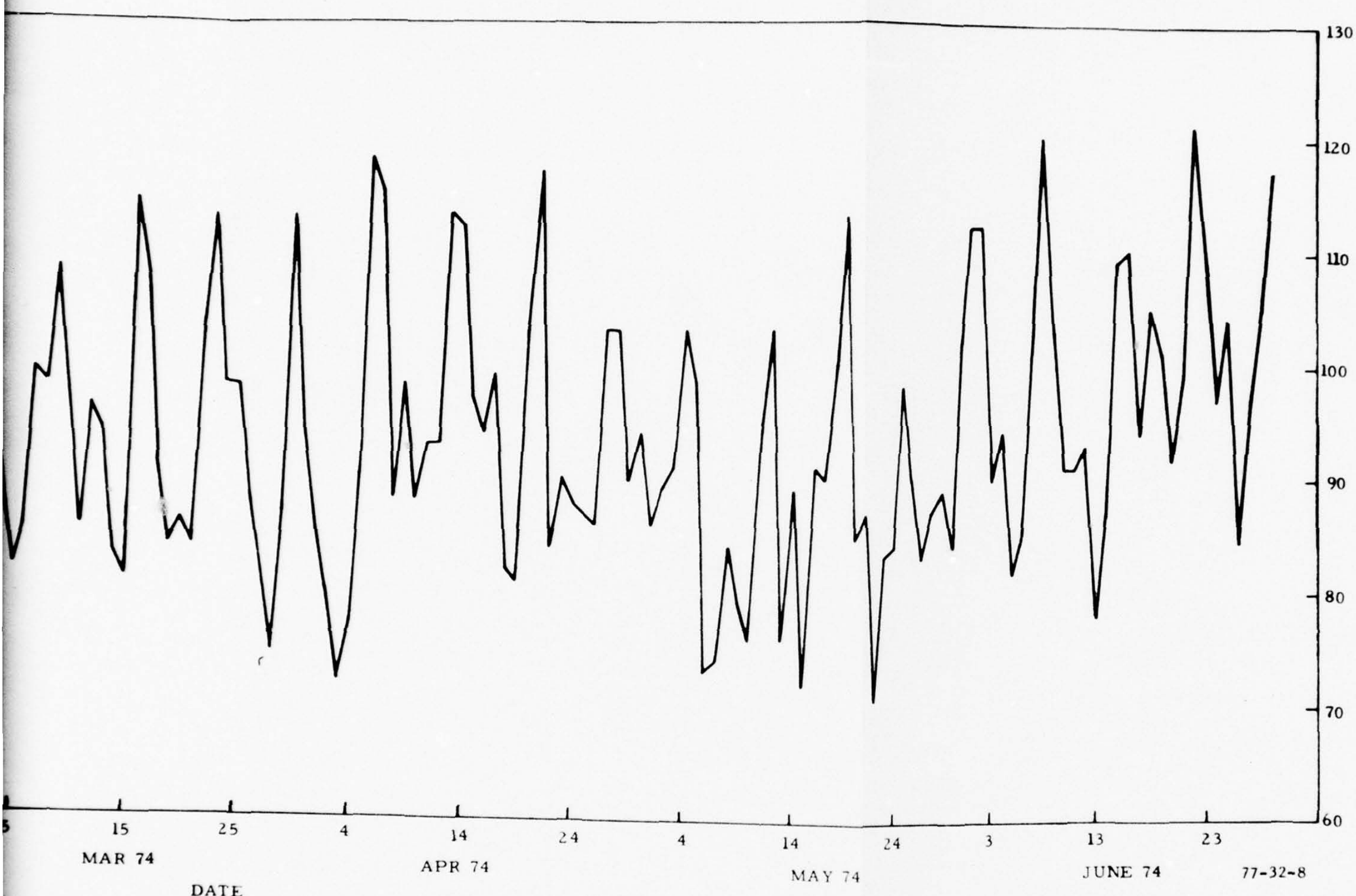


FIGURE 8. DAILY TRAFFIC COUNT OBSERV



8. DAILY TRAFFIC COUNT OBSERVED DURING DATA COLLECTION IN CEP

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Table 5 shows that westbound and eastbound traffic flows do not balance. Research into this question revealed that of the 990 extra westbound flights, 415 were military flights on missions designed to return the aircraft to the mainland United States in some way other than through the CEP. The remaining excess westbound flights were principally regularly scheduled commercial aircraft the routes of which led from Hawaii to the Orient and thence back to the mainland United States while remaining outside the area of the CEP.

Table 5 makes clear the fact that CEP users do not consider all routes equally preferable. The data indicate that CEP users have a strong preference for Alfa and Bravo routes, while North and South routes serve to handle overflow demand. During the collection of flight planning data, both commercial and military users indicated that, in general, their frequent use of North and South routes was based not upon optimum flight planning dictates, but rather upon the experience that acceptable flight levels on these routes were often available at the required time.

The daily traffic count of flights in CEP during the data collection period is shown in figure 8. Viewed as a time series, the daily traffic can be seen to be periodic of period approximately 7 days. This periodicity suggests that the number of scheduled flights tended to heavily influence the daily count, and this fact was confirmed by examination of the mix of scheduled and all other types of flights on specific days. While the series is not long enough to confidently estimate long-term trends or lengthy periodicities in the data, it does appear that seasonal effects are present in the March-to-early-April and late May-to-June time periods corresponding to the Easter and early summer vacation times. Analysis of the flights on days during these two periods indicates that above average charter flight traffic existed in the CEP.

Figure 9 presents, by Greenwich Mean Time (GMT), the percent of eastbound and westbound aircraft entering the CEP over their inbound oceanic gateways. The hourly percent entries into the CEP were determined by first grouping all aircraft observed during the data colleciton period by direction of flight, counting the number of aircraft within each of these two totals passing their inbound oceanic gateways during each of the 24 1-hour periods, and finally dividing these counts by the observed number of aircraft. Since the inbound to-outbound gateway flight time of a CEP aircraft is 3.5 to 4 hours, the relative positions of the various eastbound and westbound peak traffic densities indicate that the traffic flow at any given time of heavy system utilization is not preponderantly in one direction.

<u>Existing CEP System Users</u>. Aircraft type is useful in describing the chacteristics of the CEP user population. Using the ATC facility data, the aircraft type for each flight in the CEP during the data collection period was tabulated. The results of this compilation are presented in table 6.

The "Other" category in table 6 consists of sundry nontransport military aircraft, such as fighters and bombers, as well as infrequently seen commercial and general aviation turbojet aircraft. Military users of the CEP constituted about 14 percent of the population (C135, C141, C5 plus approximately half of the "Other" category). Of the commercial users of the system (B707, B720, B747, DC8, and DC10), the vast majority are regularly scheduled passenger or

cargo flights. Sampling of various days during the data collection period indicated that the number of nonscheduled commercial flights was positively correlated with daily flight count and that, as a proportion of daily flight count, nonscheduled commercial aircraft constituted 7 to 14 percent of the system users.

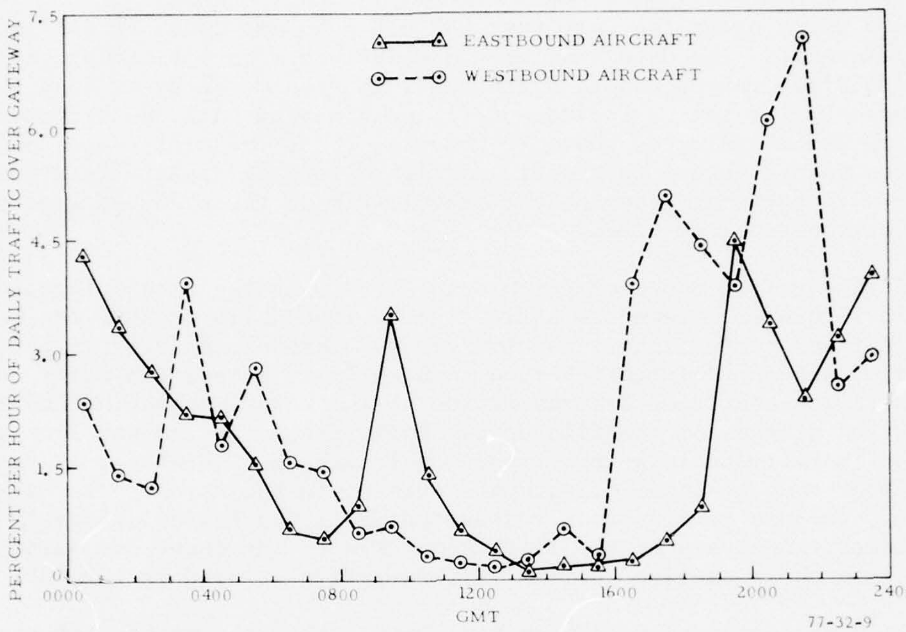

FIGURE 9. TRAFFIC DENSITY OBSERVED OVER INBOUND GATEWAY IN CEP

TABLE 6. AIRCRAFT TYPE BY PERCENT OF TOTAL SAMPLE, DECEMBER 15, 1973, TO JUNE 30, 1974

Aircraft Type	Percent of Total Sample
B707	21.8
B720	5.9
B747	33.8
KC135	2.3
C141	9.3
C5	1.5
DC8	11.6
DC10	12.1
Other	1.7

The profile of user navigation systems can also be reasonably well determined from aircraft type. The newer wide-body aircraft (B747, DC10, C5) were INS-equipped. Of the remaining military aircraft, the C141 utilized Doppler-with-computer in conjunction with LORAN C or CONSOLAN, while the KC135 and "Other" military aircraft made use of onboard hybrid systems. Approximately one half of the DC8's were INS-equipped, while the remaining DC8's and most of the B707's and B720's used Doppler-with-computer in conjunction with LORAN A. Hence, during the data collection period about 53 percent of the CEP users employed INS as the primary method of navigation, while nearly 34 percent depended upon a Doppler-LORAN A combination, 9 percent upon Doppler-LORAN C/CONSOLAN, and the remainder upon some onboard hybrid system.

DATA COLLECTION PROGRAM.

The four types of data pertinent to the estimation of collision risk and cost model parameters are aircraft position measurements, ATC facility data, CEP flight crew survey form, and commercial and military flight planning data. Eact of these types of data was obtained from a different source. The details of the collection and processing of the various data sets are detailed below and in appendix B.

AIRCRAFT POSITION MEASUREMENTS. CEP collision risk model overlap probabilities as well as relative along-track and crosstrack velocities were estimated from position measurements of aircraft navigating in the track system. The measurements were made with secondary surveillance radar (SSR) at five different locations, and these measurements were recorded in either of two modes, automatic or manual. In the automatic mode, the aircraft's slant range, azimuth, detected azimuthal width or runlength, and time of detection were digitally recorded directly onto magnetic tape for each radar scan during which the aircraft was within SSR coverage. In the manual mode, an air traffic controller recorded, on a specially designed form, his estimate of a CEP aircraft's lateral deviation from assigned course as the aircraft first came into radar coverage after transiting the track system. In both modes, determination of the specific aircraft for which measurements were made was effected by recording identifying data contemporaneously with the position measurements. This identification was done for automatically-recorded data by including on the tape the aircraft's ATC-assigned transponder code. Each aircraft's assigned transponder code was saved as part of the ATC facility data and subsequent processing matched the transponder code in the automatically recorded data to a flight number. In the manual mode, the controller recorded the aircraft's flight number immediately after writing down his estimate of deviation.

Table 7 summarizes the locations and elevations of the SSR's used for aircraft position measurement, the ARTCC's involved, the type of position measurements made, sample sizes obtained, and the periods during which position measurements were made. All SSR's associated with ARTCC's were operational enroute ATC radars. The Oakland ARTCC monitored North and Alfa route using the Oakland radar, with the Paso Robles radar serving as an auxiliary when required. The Los Angeles ARTCC observed deviations on Bravo route using the Mt. Laguna and Paso Robles radars and on South route employing the Los Angeles radar.

TABLE 7. SUMMARY OF AIRCRAFT POSITION MEASUREMENT DATA COLLECTION

SSR Location	SSR Latitude/ Longitude	SSR Elevation (feet)	ARTCC	Type of Position Measurements	Number of Measurements	Period of Data Collection
Oakland CA	37°31'44"N/ 122°25'35"W	2012	Oakland	Manual	3435	Dec. 15, 1973- June 30, 1974
Paso Robles CA	35°23'44"N/ 120°21'12"W	3658		Automatic	1080	Dec. 15, 1973- June 30, 1974
Mt. Laguna CA	32°52'33"N/ 116°24'51"W	5966	Los Angeles	Manual	4147	Dec. 15, 1973- June 30, 1974
Los Angeles CA	33°44'48"N/ 118°20'09"W	1540		Automatic	529	
Mount Kaala HA	21°30'39"N/ 158°08'42"W	4025	Honolulu	Manual	8181	Dec. 15, 1973- June 30, 1974
				Automatic	2832	March 16, 1974- June 30, 1974
Pahoa HA	19°32'37"N/ 154°58'32"W	150	--	Automatic	2555	March 1, 1974- June 27, 1974
Ocean Station November	30°N/ 140°W	0	--	Automatic	3,543	Dec. 15, 1973- Jan. 5, 1974
						Feb. 21, 1974- March 13, 1974
						April 27, 1974 May 17, 1974
						June 11, 1974- June 30, 1974

At the western end of the CEP, the Honolulu ARTCC made position measurements on North, Alfa, and Bravo route aircraft using the Mt. Kaala SSR. Since the Mt. Kaala radar did not provide coverage of South route, a United States Air Force mobile radar was positioned at Pahoa on the island of Hawaii in order to provide coverage of this route. The mobile radar was considered to possess accuracy at least comparable to the Mt. Kaala SSR and was flight-checked and calibrated by the FAA prior to being employed in data collection.

In order to obtain data on aircraft navigation in the middle of the CEP, an automatic mode data collection system was interfaced with the SSR aboard OSV November. The OSV's nominal station was at a position approximately midway between California and Hawaii and halfway between the projection of Alfa and Bravo routes on the surface of the earth. While the principal mission of OSV November was search and rescue, which resulted in interruptions of data taking, it was possible to record track data for more than 3,500 aircraft during four periods when November was on station. Although the SSR aboard the OSV was not intended for a precision ATC application, the recorded position measurements proved to be adequate for collision risk model parameter estimates. One problem associated with using OSV November for data collection was the difficulty of determining the ship's location so that aircraft target detections could be referenced to some fixed grid. This problem was solved by employing a United States Navy satellite-based position-fixing system, TRANSIM, aboard OSV November. The system was tested at dockside in Long Beach, California, during December 1973 and found to have a static mean error of position fixing approximating 50 feet. Data supplied by Johns Hopkins University's Applied Physics Laboratory, which maintained TRANSIM for the Navy, indicated that mean errors of position fixing would not exceed 300 feet when OSV November was executing normal maneuvers while on station. The TRANSIM system permitted very accurate updates of the OSV November's position every 50 to 55 minutes, and these fixes were supplemented with onboard navigation information to obtain continuous plots of November's location during data collection periods.

Distribution of Lateral Deviation From Course. The objective in collecting data descriptive of the distribution of lateral deviation from course is to characterize, statistically, navigation performance by aircraft in the CEP. Since it is necessary to have deviation measurements made by sensors which are independent of the aircraft (that is, by SSR's), the lack of complete coverage of the CEP by independent measuring devices precludes obtaining deviation measurements throughout the system. Under the assumption that an aircraft's lateral deviation from course is largest at the end of its flight, the problem of lack of coverage is circumvented by measuring the lateral deviation of an aircraft as it is inbound to landfall from the track system. The main danger with using land-based SSR's in data collection is that the aircraft being observed has already begun to use more accurate short-range navigation aids in order to correct any lateral course-keeping error when it is first observed. In order to guard against the possibility that navigation system transition would contaminate the observed errors and render them useless as descriptive of oceanic navigation, the coverage patterns of all land-based SSR's used in the data collection programs were checked against the coverage patterns of those land-based navigation aids which might be used by CEP aircraft. This check determined that CEP aircraft would have little, if any, short-range

navigation assistance prior to first radar contact. As an additional check, personnel of the FAA's Flight Standards Service who were familiar with the CEP track system and the various navigation aids in the area were consulted, and they provided opinions consonant with the coverage pattern checks. As a final, but hardly scientific, check, CEP pilots were informally questioned as to the availability of short-range navigation aids prior to first radar contact. None of the pilots indicated that any short-range navigation aids provided adequate coverage to preclude the use of lateral deviation measurements made at first radar contact. Accordingly, crosscourse error measurements made by land-based SSR's at first radar contact with aircraft inbound to landfall were used in the development of the CEP distribution of lateral deviation.

Since no short-range navigation aids were available to CEP aircraft for which deviation measurements were observed aboard OSV November, no problem existed with contamination of these data by nonoceanic navigation. However, the nominal position of the OSV was 140° West in longitude, a point requiring a heading change for aircraft on all routes, and the ship SSR was relatively less accurate than the land-based radars. Hence, it was necessary to observe lateral deviations as close to the ship as possible in order to reduce measurement error while ensuring that the point at which deviation was recorded was sufficiently far away from 140° West so that transient errors induced by turning maneuvers would not be included in the data. As a result, each aircraft's lateral deviation was observed prior to turning within an interval 25 to 75 nmi downtrack from 140° West.

Table 8 presents summary information on the distribution of lateral deviation by data collection site. The data for the Oakland and Los Angeles ARTCC's are presented separately in order to highlight the differences in percentages of large deviations observed between the northern and southern route pairs. The higher frequencies of large flying errors in the Oakland data are due principally to one CEP user, mainly on the Alfa route.

The observations of lateral deviation made at the Hawaiian data collection sites were combined. Since the Mt. Kaala radar provided coverage of North, Alfa, and Bravo routes and the Pahoa SSR was able to monitor Alfa, Bravo, and South routes, many aircraft were observed by both sensors. However, the distance from landfall at which aircraft could first be detected on the routes of common coverage, Alfa and Bravo, was not the same for each of the two radars. The radar at Mt. Kaala was able to observe aircraft inbound to Hawaii on Alfa route prior to their detection at Pahoa, while the reverse situation was true for Bravo route flights. Since, it is desirable to measure lateral deviation as far from landfall as possible, the cross-course errors from the Hawaiian sites were combined in such a manner that if an aircraft's lateral deviation had been measured by both radars, only the measurement from the radar with the longer range coverage on the assigned route was included in the data set.

The frequency of 30 nmi or greater deviations observed in Hawaii fell between that observed at Los Angeles and that at Oakland. Frequencies of 50 nmi or greater and 75 nmi or greater deviation observed in Hawaii were lower than those recorded at either California ARTCC. This reduction in the frequency of 50 nmi or greater deviations in the Hawaiian data resulted from the fact that

TABLE 8. SUMMARY OF LATERAL DEVIATION DISTRIBUTIONS BY DATA COLLECTION SITE

Data Collection Site	Direction of Flight	Number of Observations	Standard Deviation (nmi)	Percent of Lateral Deviation Greater than or Equal to: 30 nmi	50 nmi	75 nmi
Oakland	E	3,435	6.98	0.84	0.35	0.09
Los Angeles	E	4,147	6.79	0.48	0.15	0.02
Honolulu, Pahoa	W	8,478	6.34	0.58	0.05	0.01
Ocean Station Vessel November	E & W	3,543	7.90	0.76	0.17	0.03

the single CEP user whose large deviations contributed to the relatively higher frequency of large flying errors in the Oakland data demonstrated a much lower percentage of large deviations in the Hawaiian area. The reduction in this user's frequency of large flying errors in the western portion of the CEP was investigated and the better performance attributed to the availability to the user of more accurate long-range navigation aids.

The standard deviation of lateral deviations observed at OSV November is higher than at any other data collection site. This situation can be attributed to two factors. First, long-range radio navigation aids available to CEP users were least accurate and reliable in midocean, possibly resulting in less accurate course-keeping. Second, the aircraft position data recorded aboard the OSV were of considerably lower quality than that recorded at land-based sites, due to measurement noise of the radar, stability of the ship, and frequent interruptions in data taking. Much effort was expended in analyses of the OSV data in order to remedy problems observed in the position measurements, but no techniques could eradicate all problems. Every radar position measurement observed aboard the OSV was plotted, and the resulting traces were inspected to insure that all large lateral deviations would be included in the data set, because of the important impact of large flying errors on the estimation of collision risk. In each instance in which the plot of a flight indicated that the lateral error was 30 nmi or more, the deviation measurement was included in the data set in order that any errors in the processing of flights would result in conservative estimates of collision risk.

Because of problems associated with the collection of cross-course errors in the automatic mode at the land-based sites, more than half the lateral deviation measurements were made in the manual mode, and these observations showed a tendency to be recorded in increments of 5 nmi. With the exception of the entirely automatic-mode Pahoa radar observations of South route deviations, more than 99 percent of all land-based automatic-mode lateral deviations recorded had an associated manual observation. These automatic observations were used to smooth the manual data. The details of this process, as well as the summary of manual observations, are discussed in appendix B. Figure 10 presents the distributions of lateral deviation for the California, OSV, and Hawaiian data collection sites. The plots in figure 10 for the land-based data collection sites as well as the standard deviations of table 8 are results of this smoothing process.

It is of interest to examine figure 10 in light of certain assumptions of the collision risk model and some previous findings of the NAT/SPG. As is shown in appendix A, application of the collision risk model assumes that the distribution of lateral deviations consists of a core distribution, within which the bulk of the observed deviations lie, and an outlier or tail distribution made up of large flying errors which occur with low frequency. Since the distribution of lateral deviations is assumed symmetric about zero cross-course error, the remainder of the discussion will consider only the distribution of the absolute value of lateral deviations from course.

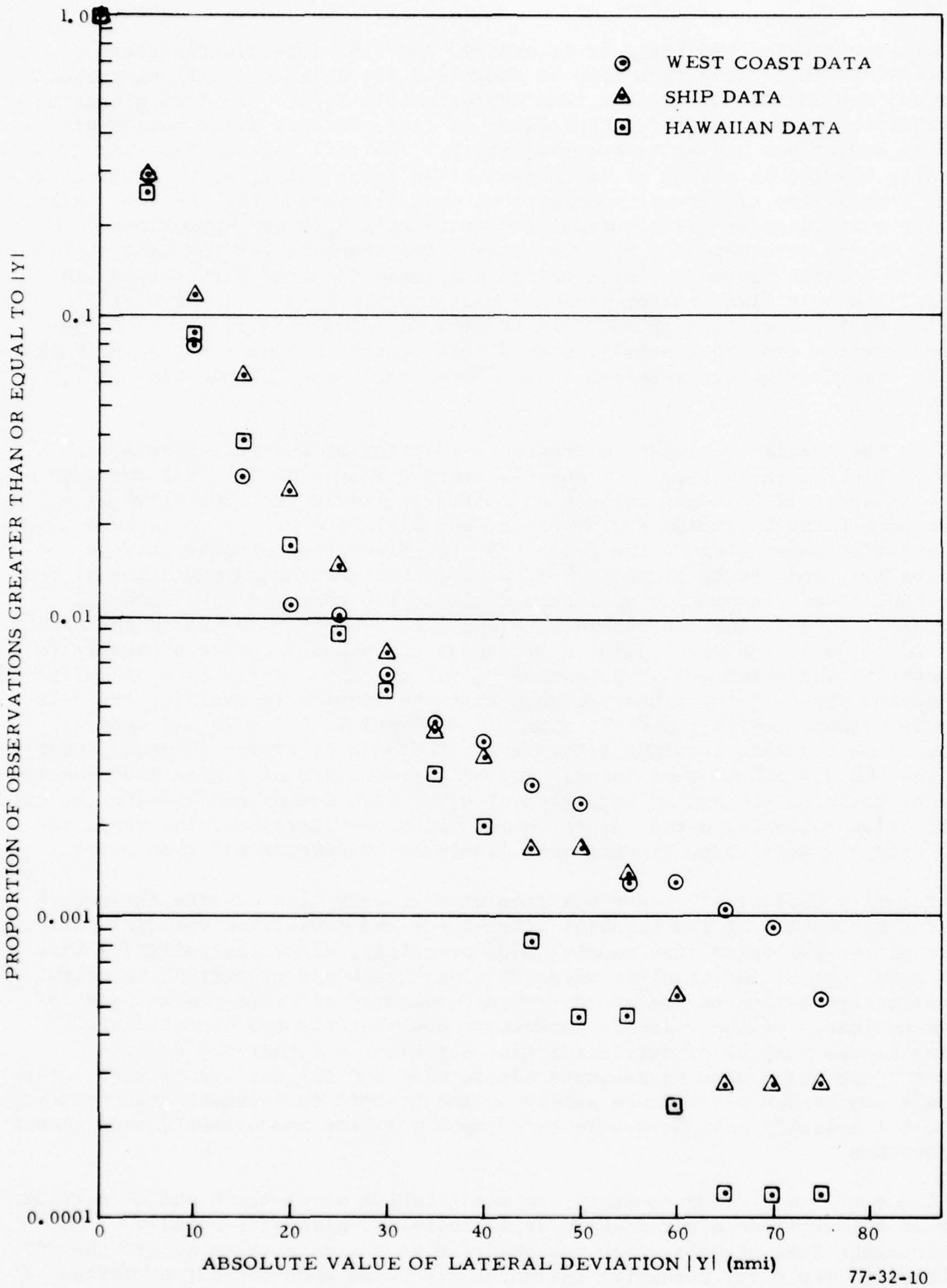

FIGURE 10. DISTRIBUTIONS OF LATERAL DEVIATION OBSERVED IN THE CEP

In collision risk methodology, it is assumed that the core distribution characterizes deviations from zero to roughly $S_y/2$, while the tail distribution describes the deviations greater than approximately $S_y/2$. The form of the core distribution is taken as First Laplacian, so that the core distribution of absolute deviations has an exponential shape. The tail distribution is typically modeled as either of two shapes. The first shape, which produces a higher probability of lateral overlap than does the second for the same tail area, is a rectangular distribution between roughly $S_y/2$ and approximately S_y (say, S_y*) and zero beyond S_y*. The alternative shape is for the tail distribution of a First Laplacian, with variance greater than the First Laplacian, used for the core distribution commencing at roughly $S_y/2$. In terms of absolute deviations, this second form is also an exponentially shaped curve beginning where the exponentially shaped core ceases. These two shapes of the outlier distribution are referred to as "level tail" and "exponential tail," respectively.

Denoting the cumulative relative frequency function of absolute lateral deviations by $F(|Y|)$, the points of figure 10 are the values of $1-F(|Y|)$ for each of the three areas of CEP data collection. If $F(|Y|)$ were the cumulative of a theoretical First Laplacian distribution, the plot of $1-F(|Y|)$ would be a straight line commencing at the point $|Y| = 0$, proportion of observations equaling 1.0, and having slope $-\sqrt{2}\,\sigma$, where σ is the standard deviation of the First Laplacian. Inspection of figure 10 indicates that the data from all three areas roughly follows such a straight line from $|Y| = 0$ nmi to the area $|Y| = 20$ to 30 nmi at which point a different curve would appear necessary to characterize the relationship between $1-F(|Y|)$ and $|Y|$. While lack of sufficient data beyond about 70 nmi makes adequate characterization impossible, the relationship between $1-F(|Y|)$ and $|Y|$ from $|Y| = 20$ nmi to $|Y| = 70$ nmi would appear to be a second straight line. Thus, the data of figure 10 would suggest that the CEP distribution of lateral deviations consists of a core distribution between, roughly, ± 30 nmi of zero lateral error with deviations outside the core distribution following a tail distribution which, at least over the range for which data are available, appears more likely to be exponential than level.

Velocity Estimates. Radar position measurements also provide the source data for estimation of the relative along-track and crosstrack velocity parameters of the collision risk model. More precisely, since the collision risk model makes use of the absolute value of along-track and crosstrack velocity, the parameters estimated are speeds. Radar-measured aircraft tracks used to derive estimates of the velocity parameters must satisfy two conditions: (1) the tracks must be of sufficient time duration such that the derived estimates are based upon an adequate sample size and (2) the tracks must reflect aircraft navigation performance solely in the oceanic environment under study. Hence, all velocity estimates were based upon position measurements made aboard OSV November.

The model-required parameters are the relative along-track and crosstrack speed of a coaltitude aircraft pair as it loses all planned separation. No such complete loss of separation was observed in the data taken aboard the OSV. As a result, the model parameter estimates are based upon the extrapolation of

observed relationships between relative separation change and relative speed. The fact that the velocity estimates required by the model are relative (between pairs of aircraft within radar coverage at approximately the same time) rather than absolute somewhat lessens any effects upon the quality of the estimates resulting from radar-induced biases in position measurements.

Ideally, relative velocity measurements should be made based upon coaltitude aircraft which are abreast on adjacent tracks. Given the limited number of aircraft tracks observed aboard OSV November, this ideal was compromised in order to obtain a sample of relative velocity measurements sufficiently large to keep sampling errors under control. As a result, both the coaltitude and abreast requirements for an aircraft pair were relaxed somewhat in the accumulation of relative velocity data. A further enhancement of sample size was obtained by making the reasonable assumptions (substantiated by the data), that an aircraft pair is as likely to be diverging as converging laterally and that an aircraft pair is as likely to gain as to lose lateral separation. It follows that absolute values of converging and diverging relative velocities may be lumped together as a function of the absolute value of separation lost or gained, thus increasing the sample size used in the estimation process.

Estimates of relative crosstrack speed. For purposes of velocity estimation, 50-nmi length intervals of aircraft tracks recorded aboard the OSV were processed. Since the four tracks in the CEP system had heading changes at 140° W, the intervals were positioned sufficiently far from this longitude in order to avoid turn effects in the data and yet close enough to the nominal position of the OSV to assure that the best quality radar measurements were used. Thus, for eastbound flights the interval commenced 75 nmi downtrack from 140° W to the west and for westbound flights 75 nmi downtrack to the east of 140° W. Within the appropriate interval, aircraft tracks for which adequate radar data existed were processed to obtain the algebraic deviation from course (positive for northerly errors and negative for those to the south of track) and crosstrack velocity (positive if northerly and negative if southerly).

After single aircraft position and velocity data were obtained, aircraft were combined in pairs in order to relate separation loss to cross-course speed. Two sets of criteria for altitude and longitudinal separation were imposed in order to include an aircraft pair in the relative crosscourse speed data. The first set of criteria was that two same-direction aircraft were assigned to flight levels within 2,000 feet of each other, and that their 140° W crossing times were within 60 minutes of each other. The second set of criteria required no more than 4,000 feet altitude separation between the aircraft and no more than 120 minutes between 140° W crossing times. In each set of data, no aircraft was permitted to be a member of more than one pair in order to obviate the possibility of introducing correlations into the data. The relationship of relative crosstrack speed to separation lost or gained for the two sets of criteria is shown in tables 9 and 10, which display the observed counts of aircraft pairs having the various combinations of separation loss or gain and relative crosstrack speed. The last column in each of the tables presents the mean relative crosstrack speed observed for each interval of separation loss or gain. It will be noted that for small values of separation loss or gain the mean relative crosstrack speed is an increasing function of separation

TABLE 9. COUNTS OF RELATIVE CROSSTRACK SPEED AS FUNCTION OF LOSS OR GAIN IN SEPARATION FOR PAIRS OF ADJACENT TRACK AIRCRAFT WITH AT MOST 60 MINUTES LONGITUDINAL SEPARATION AND WITH AT MOST 2,000 FEET ALTITUDE SEPARATION

Loss or gain of separation (nmi)	Relative crosstrack speed (knots)												
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50	50-55	55-60	Mean
55 - 60													
50 - 55													
45 - 50								1					37.13
40 - 45													
35 - 40				1									15.02
30 - 35		1				1							17.50
25 - 30	2				1	1			1			2	38.81
20 - 25	2	1		3	1	1							14.01
15 - 20	2	3	2	1	1	2			2	1	1		22.43
10 - 15	5	6	6	1	2	5	1	3	2	1		1	20.55
5 - 10	14	5	13	14	8	5	2	1	1	2		5	19.65
0 - 5	48	25	35	17	17	7	8	4	9	4	1	4	16.49

TABLE 10. COUNTS OF RELATIVE CROSSTRACK SPEED AS FUNCTION OF LOSS OR GAIN FOR SEPARATION FOR PAIRS OF ADJACENT TRACK AIRCRAFT WITH AT MOST 120 MINUTES LONGITUDINAL SEPARATION AND WITH AT MOST 4,000 FEET ALTITUDE SEPARATION

Loss or gain of separation (nmi)	Relative crosstrack speed (knots)												
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50	50-55	55-60	Mean
55 - 60													
50 - 55													
45 - 50								1				1	47.39
40 - 45	1		1	1	1								13.09
35 - 40													
30 - 35	1							1		1			29.67
25 - 30	1		1		1				2	1			29.13
20 - 25	2	4	6	3	1	1	2		1				15.90
15 - 20	3	3	5	1	3	1	2	2	2		1	3	27.53
10 - 15	7	6	9	10	2	6	3	2	4			1	19.18
5 - 10	18	23	21	18	11	11	6	4	2	1		7	18.55
0 - 5	64	45	47	20	28	11	15	11	8	1	4	7	16.59

loss or gain. As the separation loss or gain increases, with concomitant decrease in the observed number of aircraft pairs exhibiting the loss or gain, the relationship of mean crosstrack speed to separation loss or gain is less clear.

Figures 11 and 12 present least-squares straight-line fits of the mean values of relative crosstrack speed as a function of separation loss or gain for the data of tables 9 and 10, respectively. The horizontal lines in the figures are the mean values of crosstrack speed from tables 9 and 10. Prediction, based upon these lines, of the relative crosstrack speed when all planned lateral separation is lost provides the relative lateral speed parameter of the model. The regressions were performed using the grouped data of tables 9 and 10 by allocating the observed frequency of aircraft pairs in each interval of separation loss or gain to the midpoint of the interval, and assigning each pair the mean relative speed computed for the interval.

Tables 11 and 12 present the crosstrack speed as a function of crosstrack error for the single aircraft which form the pairs of tables 9 and 10. As can be seen, crosstrack speed is positively correlated with crosstrack error. This is as expected, since an aircraft's cross-course drift must be larger in order to produce a larger lateral error, and since if an aircraft detects that it has made a cross-course error, it is likely that a velocity in the direction of course centerline will be applied in proportion to the error.

Estimates of relative along-track speed. As with relative crosstrack speeds, the mean relative along-track speed required in the model is that existent when a coaltitude aircraft pair assigned to adjacent tracks loses all planned lateral separation. However, since along-track velocity is almost independent of the previous history of flight, it is valid to select for estimation of relative along-track speed pairs of aircraft assigned to the same track and flight level. The choice of same-track aircraft is preferable, since any effects on velocity due to winds are more likely to be cancelled out in the computation of relative estimates of along-track speed. Again, a compromise must be reached between the desire to have pairs close together and the need for adequate sample size. One set of aircraft pairs was assembled using the criteria that both aircraft were assigned to the same track and flight level and that the interpair longitudinal separation was no greater than 60 minutes. A second set was generated by relaxing the longitudinal separation criterion to 120 minutes. Table 13 presents for the two sets the number of aircraft pairs with relative along-track speeds in intervals of 10 knots and also the model-required parameter estimate, the mean along-track speed.

Table 11 shows a number of pairs with large relative speeds. These large values may be explained in part by the fact that a small proportion of error in one aircraft maintaining an along-track velocity leads to a large relative velocity difference with respect to a similar speed aircraft. However, the major contributor to the large speed differences is the wide mix of speed classes amongst CEP aircraft. As an example, the B747 type of aircraft typically flew the CEP at mach 0.84, while the C141 flew at mach 0.74.

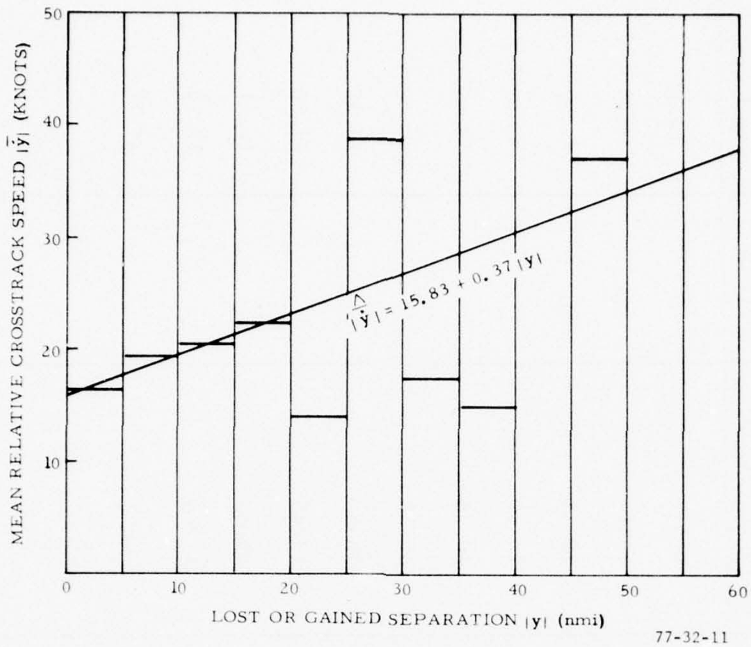

FIGURE 11. MEAN RELATIVE CROSSTRACK SPEED AS A FUNCTION OF LATERAL SEPARATION LOST OR GAINED FOR 60-MINUTE, 2,000 FEET ALTITUDE PAIRS

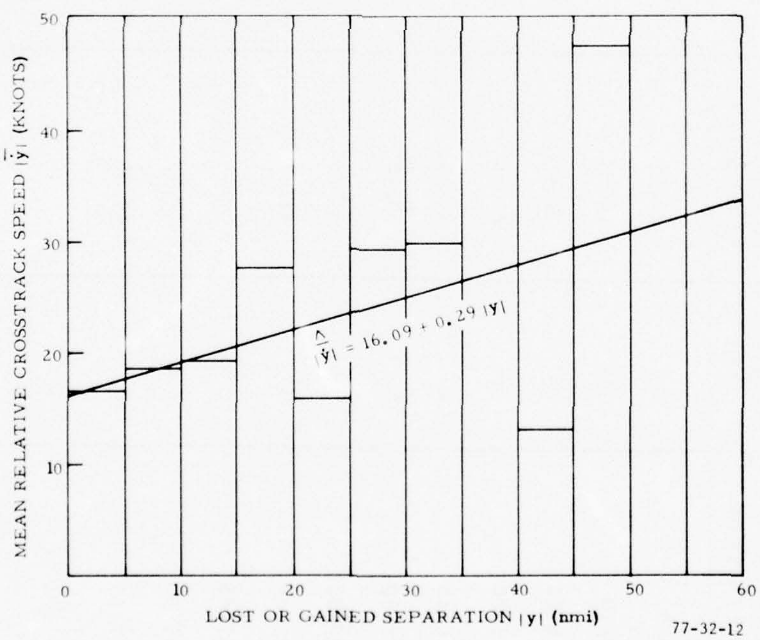

FIGURE 12. MEAN RELATIVE CROSSTRACK SPEED AS A FUNCTION OF LATERAL SEPARATION LOST OR GAINED FOR 120-MINUTE, 4,000 FEET ALTITUDE PAIRS

TABLE 11. MEAN CROSSTRACK SPEED AS FUNCTION OF ABSOLUTE VALUE OF LATERAL DEVIATION FOR SINGLE AIRCRAFT USED IN 60 MINUTE LONGITUDINAL, 2,000 FEET ALTITUDE PAIRS OF TABLE 9

Absolute Value of Lateral Deviation	Number of Aircraft	Estimate of Mean Across-Track Speed
0-5	448	14.36
5-10	118	16.81
10-15	32	22.18
15-20	19	23.65
20-25	6	18.95
25-30	5	23.92
30-35	0	-
35-40	1	61.65
40-45	0	-
45-50	1	27.79
50-55	2	44.08

TABLE 12. MEAN CROSSTRACK SPEED AS FUNCTION OF ABSOLUTE VALUE OF LATERAL DEVIATION FOR SINGLE AIRCRAFT USED IN 120 MINUTE LONGITUDINAL, 4,000 FEET ALTITUDE PAIRS OF TABLE 10

Absolute Value of Lateral Deviation	Number of Aircraft	Estimate of Mean Across-Track Speed
0-5	683	14.02
5-10	194	16.04
10-15	61	21.59
15-20	28	24.06
20-25	7	32.49
25-30	9	20.38
30-35	1	14.39
35-40	2	49.50
40-45	2	16.11
45-50	1	27.79
50-55	2	44.08

TABLE 13. RELATIVE ALONG-TRACK SPEED

Relative Along-Track Speed (Knots)	Same-Direction/ Route Coaltitude Pairs within 60 Minutes Longitudinally	Same-Direction/ Route Coaltitude Pairs within 120 Minutes Longitudinally
0-10	72	96
10-20	62	85
20-30	26	47
30-40	27	48
40-50	15	25
50-60	16	23
60-70	6	11
70-80	3	3
80-90	4	9
90-100	2	2
100 or more	10	15
Mean	27.802	28.994

ATC FACILITY DATA. During the data collection period, records of CEP aircraft flights were gathered on a daily basis at the oceanic ATC control sectors in Oakland and Honolulu. For each CEP flight, the data consisted of (1) flight plan filed route and flight level with any enroute changes effected, (2) times across required CEP reporting points (inbound and outbound gateway plus intersections of the assigned route with longitudes 130° W, 140° W, and 150° W), (3) mach number if assigned, (4) oceanic transponder code, and (5) aircraft type. The ATC facility data provided the source data for estimation of risk model parameters descriptive of the amount of time during which a typical aircraft pair was proximate and thus exposed to the hazard of a collision.

The only types of proximate aircraft pairs found in the existing CEP track structure were same-direction lateral and opposite-direction vertical. Furthermore, the vertical collision risk in the CEP is based upon that of the NAT/SPG and is thus that estimated value. Hence, only the same-direction lateral proximity time had to be estimated from the ATC facility data. When estimating longitudinal collision risk, proximity time is viewed from a perspective slightly different from that used in the calculation of lateral and vertical collision risk. Nevertheless, the ATC facility data also provided the source data for longitudinal proximity time estimation.

Same Direction Lateral Occupancy. In order to estimate E_y(same), the same-direction lateral occupancy, a process similar to that employed by the NAT/SPG was used. Twenty-five days were selected from the data collection period. The days were chosen to give a representative sample of days of the week and months of the data collection period, and to provide a reasonable span in the observed daily traffic counts. For each day, all flights were examined to ensure that no erroneous reporting times existed in the flight progress information. At this point, a computer program looked at the time that each aircraft reported crossing 130° W and determined the number of coaltitude aircraft on laterally adjacent tracks which reported crossing 130° W within 15 minutes of this time. The sum of such counts for all aircraft was multiplied by 2 and was divided by the total number of aircraft crossing 130° W for the day. Similar ratios were developed for the 140° W and 150° W required reporting points. Finally, the average of the three numbers was computed and used as the estimate of E_y(same) for that day.

Figure 13 presents the sample of 25 estimated occupancies and also the least squares straight-line fit of same-direction lateral occupancy as a function of observed daily traffic count. Similar estimates for the three laterally adjacent route pairs of the original CEP were also made for the 25-day sample and are presented with corresponding least squares linear fits in figure 14.

Tables 14 and 15 present the slope and intercept parameters of the regression lines of figures 13 and 14 along with the standard errors of the estimated slopes.

Longitudinal Collision Risk Parameter Estimates. Aircraft pair proximity in the calculation of longitudinal collision risk is defined in a manner different from that in the lateral case. In place of the lateral occupancy, the

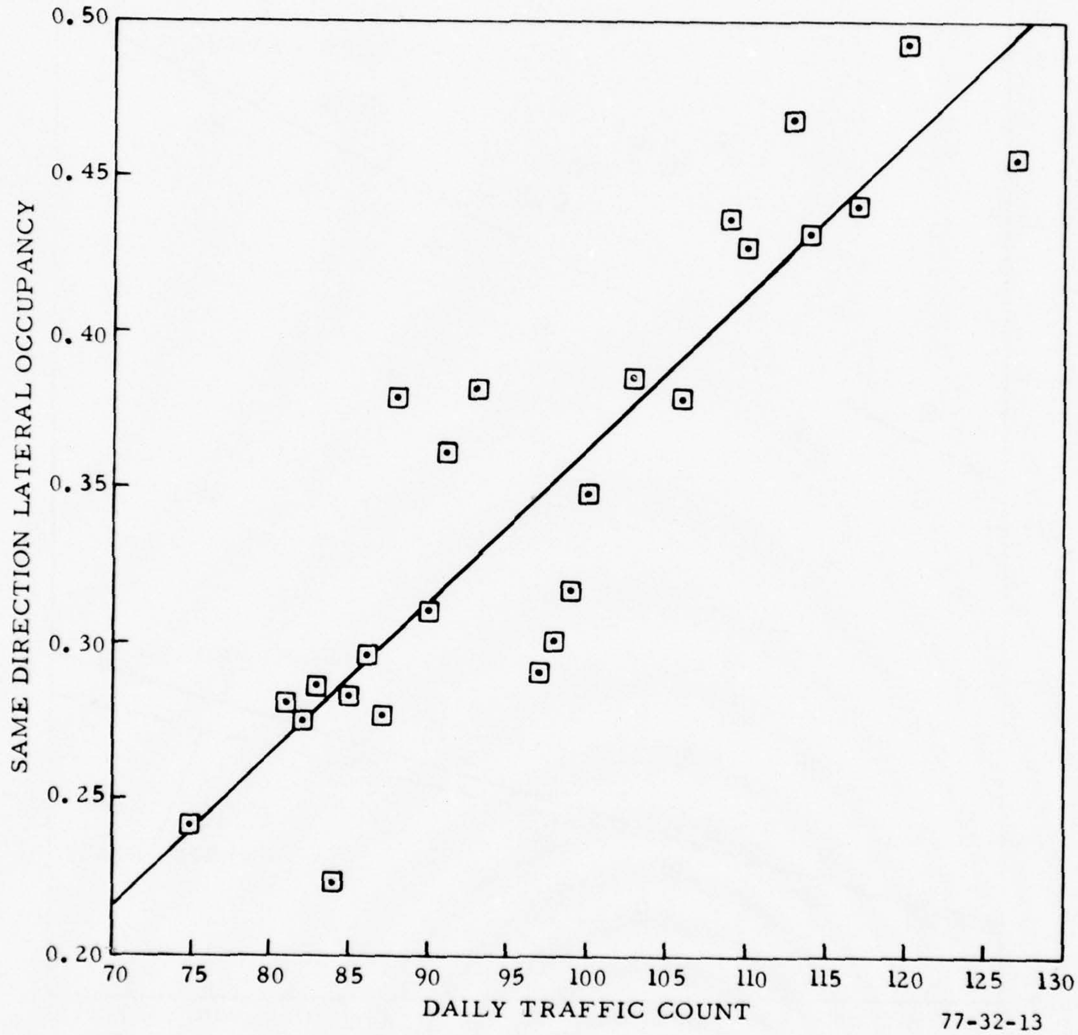

FIGURE 13. EXISTING CEP SYSTEM ESTIMATES OF SAME-DIRECTION LATERAL OCCUPANCY AS A FUNCTION OF DAILY TRAFFIC COUNT

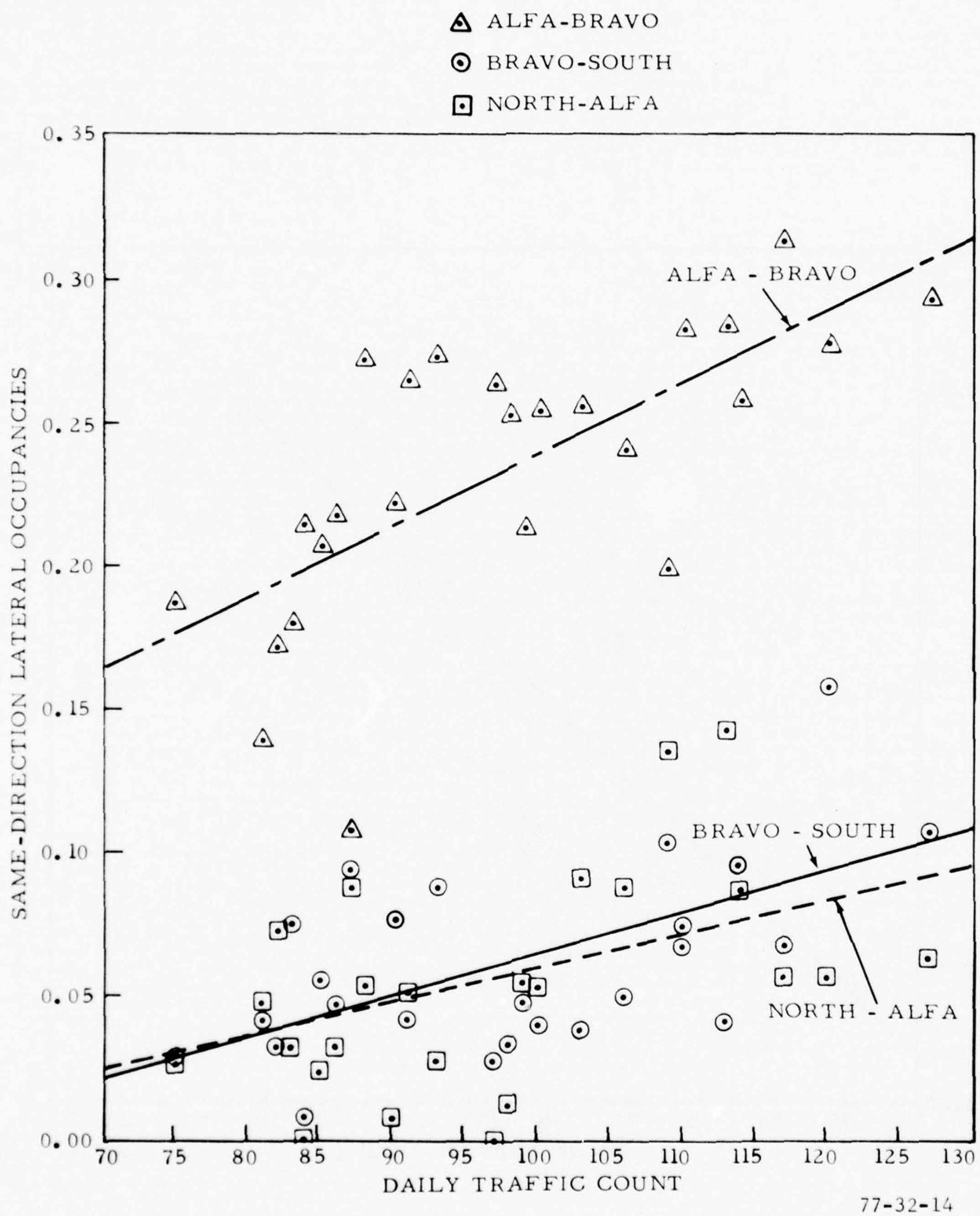

FIGURE 14. EXISTING CEP SYSTEM ESTIMATES OF SAME-DIRECTION LATERAL OCCUPANCY AS A FUNCTION OF DAILY TRAFFIC COUNT FOR ROUTE PAIRS

TABLE 14. PARAMETER ESTIMATES OF LINEAR FIT OF LATERAL SAME-DIRECTION OCCUPANCY AS FUNCTION OF DAILY TRAFFIC COUNT FOR THE EXISTING CEP SYSTEM

Parameter	Estimate	Standard Error of Estimate
Slope	0.00490	0.00007
Intercept	-0.12682	-----

TABLE 15. PARAMETER ESTIMATES OF LINEAR FIT OF LATERAL SAME-DIRECTION OCCUPANCY AS FUNCTION OF DAILY TRAFFIC COUNT FOR ROUTE PAIRS OF THE EXISTING CEP SYSTEM

Parameter	Route Pair	Estimate	Standard Error of Estimate
Slope	North-Alfa	0.00117	0.00007
	Alfa-Bravo	0.00248	0.00008
	Bravo-South	0.00145	0.00006
Intercept	North-Alfa	-0.05730	-----
	Alfa-Bravo	-0.00817	-----
	Bravo-South	-0.08008	-----

parameter of interest is $E_x(t)$, the average proportion of same-route coaltitude aircraft pairs with exactly t minutes initial longitudinal separation after correction for mach number difference. A second parameter of import is $P_x(t)$, the probability that an aircraft pair will lose exactly t minutes initial separation which is not accounted for by mach number difference. In NAT/SPG collision risk methodology, the product $P_x(t)\ E_x(t)$ when summed over all values of initial separation, t, and properly scaled (see appendix A for details of the scaling) is taken to be the probability of longitudinal overlap, πx.

In order to estimate $E_x(t)$, the interarrival times of same-route, coaltitude pairs of aircraft were examined at their first required longitudinal reporting point in the CEP (130° W for westbound aircraft and 150° W for eastbound aircraft). The first longitudinal reporting point rather than the entrance gateway was used, since many aircraft in the CEP were radar-vectored into the system without passing over the gateway, a factor which would reduce the size of the sample analyzed. The first required longitudinal reporting point on each route is considered to be sufficiently close to the corresponding entrance gateway to provide a reasonable threshold for measuring initial inter-pair separation. A total of 16,478 aircraft pairs were identified in the ATC facility data as candidates for initial separation examination. After correcting for mach number differences between members of each pair, those pairs with initial separations of up to 30 minutes were extracted from the data and tabulated in increments of 1 minute. The count for each separation, t, was divided by 16,478 in order to yield an estimate of $E_x(t)$. The results of this processing are presented in table 16 and displayed in figure 15.

A total of 4,706 aircraft pairs initially separated by up to 60 minutes along track were examined in order to estimate $P_x(t)$. The separation of each pair at their final CEP longitudinal reporting point (130° W for eastbound aircraft and 150° W for westbound aircraft) was determined, and the loss or gain in separation for the pair not explained by differences in mach number was tabulated. Assigning a positive sign for a separation gain and a negative sign for separation loss, the relative frequency distribution of gains and losses, displayed in figure 16, was found to be quite symmetric about zero minutes. Since this symmetry implies that a separation loss is as likely as an equivalent separation gain, the distribution was folded about zero minutes in order to provide more data for analysis of the less frequently occurring separation changes. The cumulative frequencies of the folded distribution after subtraction from 1.0 are shown in figure 17. Estimation of the distribution of $P_x(t)$ may be done from this data.

An additional parameter required for the calculation of estimated longitudinal collision risk is the average relative along-track velocity of an aircraft pair as all longitudinal separation is lost. Examination of radar tracks of aircraft which were members of pairs losing large amounts of initial along-track spacing not accounted for by mach number differences failed to uncover any pattern of the high relative velocities required to close such spacings. As a result, the average relative along-track velocities of table 13 were used in longitudinal collision risk estimation.

TABLE 16. $E_x(t)$: DISTRIBUTION OF EFFECTIVE INITIAL LONGITUDINAL SEPARATIONS AS A FUNCTION OF TIME (N=16,478)

Initial Separation (Minutes)	Frequency (A/C Pairs	$E_x(t)$
12	2	.00012
13	1	.00006
14	6	.00036
15	27	.00164
16	52	.00316
17	71	.00431
18	90	.00546
19	101	.00613
20	135	.00819
21	119	.00722
22	138	.00837
23	148	.00898
24	132	.00801
25	130	.00789
26	153	.00929
27	134	.00813
28	126	.00765
29	135	.00819
30	125	.00759

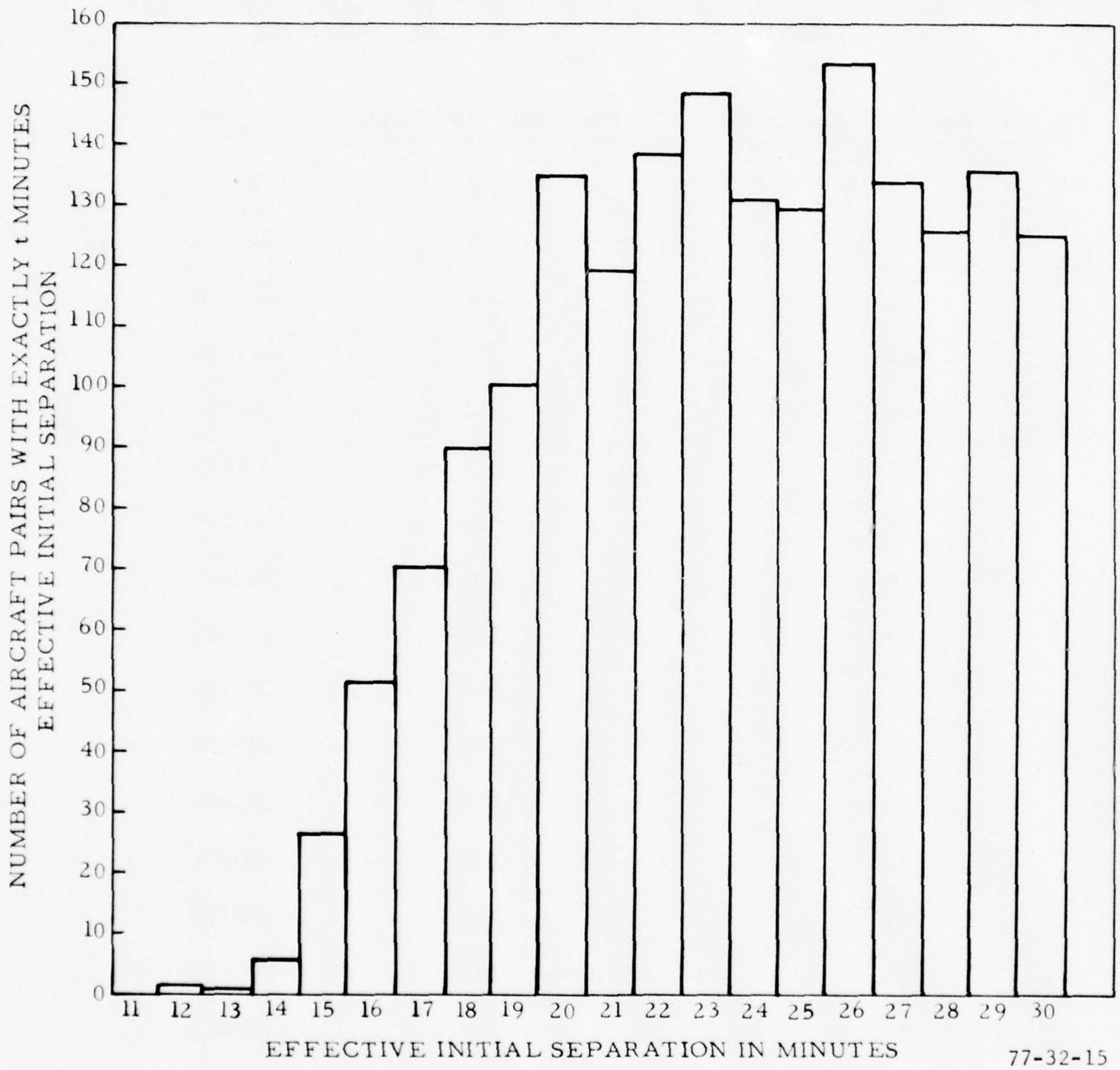

FIGURE 15. E_X (T): INITIAL EFFECTIVE LONGITUDINAL SEPARATION OF SAME-ROUTE, COALTITUDE AIRCRAFT PAIRS IN CEP

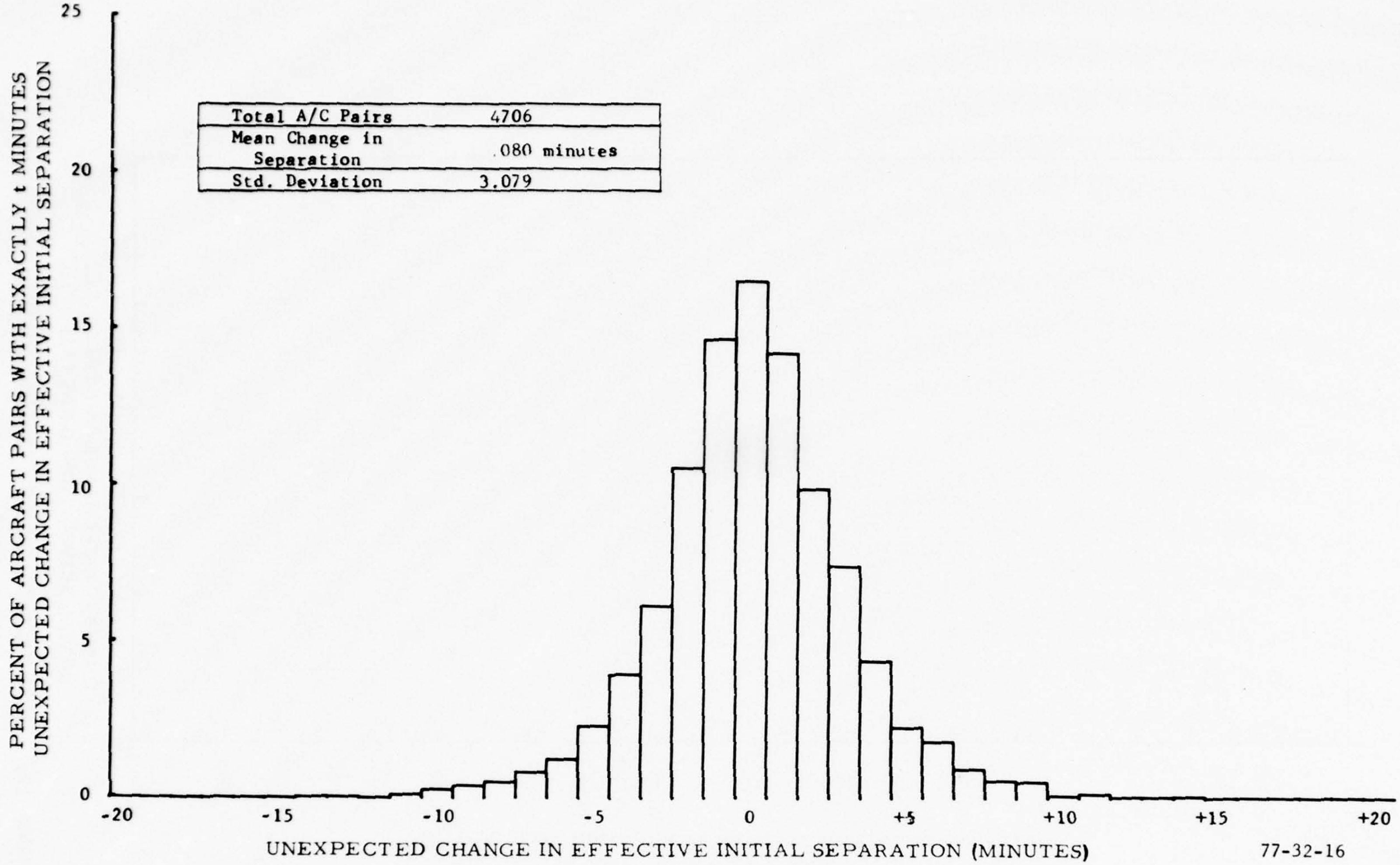

FIGURE 16. RELATIVE FREQUENCY HISTOGRAM OF UNEXPECTED CHANGES IN EFFECTIVE INITIAL LONGITUDINAL SEPARATION, EAST AND WESTBOUND TRAFFIC

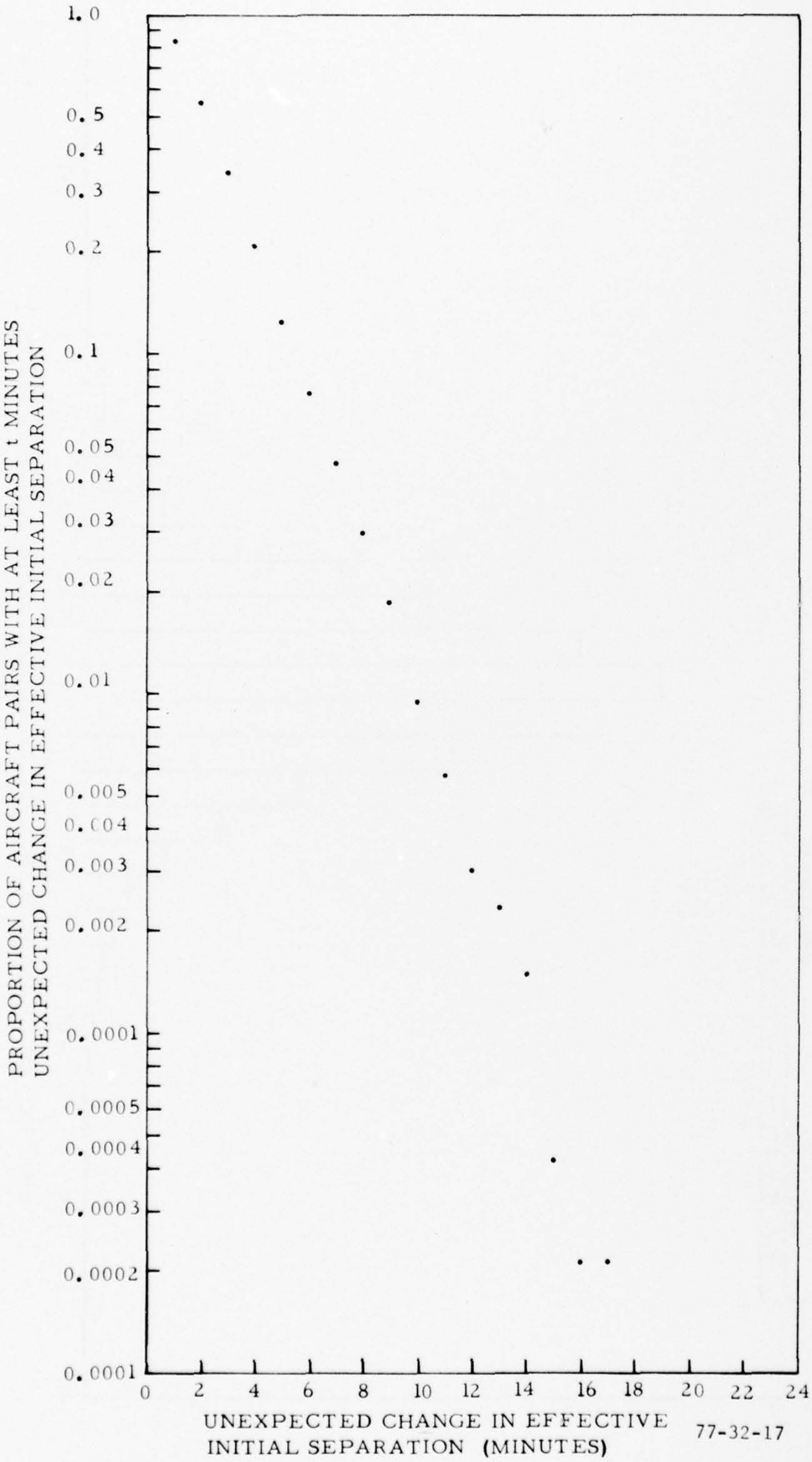

FIGURE 17. FREQUENCY CHANGE, T, IN LONGITUDINAL SEPARATION

Accuracy of Longitudinal Reporting Times. Since the estimates of same-direction lateral occupancy, $P_x(t)$, and $E_x(t)$ are based upon aircraft reported rather than independently observed longitudinal crossing times, the accuracy of these reported times has a major impact upon the quality of the estimates. In order to investigate the precision of the aircraft reported times, a sample of 905 aircraft traces from the second and third station periods of the OSV were examined in order to determine the actual times of crossing 140° W. These times were rounded to the nearest minute and the difference between the reported and actual times in minutes for each aircraft was formed. Table 17 presents the resulting range of differences between actual and aircraft-reported 140° W times and the associated number of aircraft observed with the differences. The table indicates that the large majority of reports, over 80 percent, are within at least ± 3 minutes of the actual crossing time and that only about 3 percent are in error by greater than ± 3 minutes.

TABLE 17. DIFFERENCE BETWEEN ACTUAL AND AIRCRAFT-REPORTED 140° W TIMES

Actual Minus Aircraft-Reported 140° W Time (Minutes)	Number of Aircraft Observed with Difference (Total Aircraft = 905)
-7	1
-6	3
-5	3
-4	7
-3	14
-2	44
-1	176
0	379
1	196
2	51
3	14
4	7
5	7
6	2
7	1

FLIGHT CREW SURVEY FORMS. Flight crew survey forms were distributed in the CEP during the data collection period in order to both collect information for which there was no other source and also to provide information useful in cross-checking other sources. During the 6 1/2-month data collection period, flight crew survey forms were returned for only 54.2 percent of the observed flights. It is felt that this sampling, while not as large as desired, did reasonably represent the population of users of the CEP. (In sampling studies, the dangerous assumption must be made that nonrespondents have the same characteristics as respondents. Much sampling experience is contrary to this assumption. A larger sample would have been highly valued.) A comparison of these forms

with system user profiles obtained from the other sources does not indicate any significant biasing with respect to specific operators, aircraft times, or routes utilized. Further discussion of the flight crew survey forms may be found in appendix B, with figure B-1 illustrating the form distributed to the crews.

COMMERCIAL AND MILITARY FLIGHT PLANNING DATA. In October 1974, contacts and visits were made with commercial and military users of the CEP track systems in order to gather flight planning information and gain insight into the operations of the major users of the system.

Flight plans for the eight aircraft types under two weather conditions, typical summer and typical winter, were generated for the purpose of developing fuel-burn and flight-time penalties. The weather conditions (temperature and wind deviations from standard) used in these calculations are summarized in table 18. Flight plans for two, and in some cases three different payloads were provided so that fuel burn and flight time penalties could be derived. Detailed flight plans were provided for each of the eight routes. The eight routes included the four routes of the existing system, the two composite routes, Victor and Yankee, plus two additional routes: Uniform, north of the track system, and Zulu, south of the track system. Flight plans for the two additional routes were obtained for purposes of interpolation to assess modifications to the track structure. In addition, charts showing the effect of gross weight on fuel burn were provided to assist in developing the carry cost of fuel. It was assumed for the eastern gateway of Yankee route that aircraft could be transitioned from the gateway through airspace currently restricted to military use. The transitions used between the terminals and gateways for the composite routes are listed in ATC terminology below:

Victor Route Westbound - Departure from SFO.

Drake Three Departure to Sunset then direct (240° Mag. track) to Birch-Victor route to Venture direct Magnolia thence Agate One Arrival to HNL.

Yankee Route Westbound - Departure from LAX.

Perch One Departure via control 1316 to Perch intersection (N33 52.1 W119 09.4) then direct Willow, Yankee route to Yuletide direct Banana, Banana Three Arrival to HNL.

Victor Route Eastbound - Departure from HNL.

Aku Seven Departure to Agate direct to Victor route at 27° 00'00"N and 150° 00'00"W to Birch, direct to Rainbow intersection, thence Apricot Four Arrival to SFO.

Yankee Route Eastbound - Departure from HNL.

Bluefin Three Departure to Bluefin Intersection direct to Yuletime, Yankee route to Willow, direct SXC, direct Seal Beach (SLI) to LAX.

TABLE 18. WEATHER CONDITIONS USED IN CEP SIMULATION

Temperature Deviation Over All Routes

Winter	Summer
+2°C	+7°C

Mean Wind Factors

	WINTER					SUMMER				
Flight Level	180	240	300	340	390	180	240	300	340	390
Route Segment										
LAX-HNL	-11	-17	-25	-28	-33	-6	-11	-18	-21	-26
HNL-LAX	+10	+16	+23	+26	+30	+5	+10	+17	+20	+24
SFO-HNL	-11	-17	-24	-27	-31	-6	-11	-17	-20	-25
HNL-SFO	+10	+16	+22	+25	+28	+6	+10	+16	+19	+23

Note: LAX = Los Angeles
HNL = Honolulu
SFO = San Francisco

ESTIMATES OF COLLISION RISK FOR THE CEP TRACK SYSTEM

The following sections present the estimates of lateral, composite, longitudinal, and vertical collision risk for the existing and the proposed composite CEP track systems. First, risk estimates for the existing system, together with assumptions and methods of calculation, are detailed. Then, a description of the proposed composite CEP track system and attendant estimates of collision risk are provided.

COLLISION RISK ESTIMATES FOR THE EXISTING CEP TRACK SYSTEM.

Certain assumptions regarding the geometry of the existing track system required to facilitate calculation of risks are first detailed, followed by a description of the technique employed in the estimation of lateral collision risk. Finally, model-required parameters are summarized and the resultant estimates of collision risk presented. These estimates formed the standard against which alternative composite CEP track system structures were compared on the basis of collision risk.

ASSUMPTIONS CONCERNING THE GEOMETRY OF THE EXISTING CEP TRACK SYSTEM. An assumption made in the derivation of the lateral collision risk model is that the track system under study consists of parallel, equally spaced routes. Consideration of figure 3 indicates that the geometry of the original CEP violates this assumption. since the track system consists of two route pairs which diverge from each other east of 140° W longitude. This route geometry, as well as considerations of variation in navigation performance as a function of location in the track system, led to the division of the existing CEP into portions and the calculation of lateral collision risk estimates for each portion. The lateral collision for the overall system was then computed as a weighted sum of the contribution from each of the portions.

The rationale underlying the division of a track system into disjoint portions with a separate lateral collision risk estimated for each was presented at the Fourth Meeting of the NAT/SPG (reference 5). The basis of the argument for apportionment of the lateral collision risk is that the two principal parameters in the risk model, probability of lateral overlap and lateral occupancy, are functions of long-range navigation aids, track system geometry, and variations in traffic density. Thus, an estimation of lateral collision risk based upon the local variations in these factors will be more representative than one based upon a single characterization of probability of lateral overlap and of lateral occupancy which is assumed to pertain to the track system as a whole. This principle having been applied, the CEP was divided into three portions for the purpose of estimating collision risk:

(1) Eastern portion--from the California oceanic gateways westward to one-third the distance of the oceanic routes,

(2) Western portion--from the Hawaiian oceanic gateways eastward to one-third the distance of the oceanic routes, and

(3) Central portion--the middle third of the track system.

In order to obviate the difficulty that nonparallel routes present in the application of the lateral collision risk model and to make more tractable the calculation of the probability of lateral overlap, certain simplifying assumptions were made about the geometry of the track systems in each of the portions. The assumed geometries, considered to be conservative in that they lead to somewhat higher estimation of lateral collision risk than would the actual geometries of the portions, are:

(1) The lateral separation between all adjacent routes in the western portion is 100 nmi,

(2) The lateral separation between all adjacent routes in the central portion is 100 nmi, and

(3) In the eastern portion, the lateral separation between North and Alfa routes and between Bravo and South routes is 100 nmi, while the lateral separation between Alfa and Bravo routes is 150 nmi.

Few, if any, aircraft join or leave the CEP between the California and Hawaiian gateways, and thus no substantial variations in lateral occupancy should be expected among the three portions. As a result, the overall CEP system lateral occupancy estimates of figure 13 were used for the central and western portions, while the between-route occupancies of figure 14 were used for the eastern portion.

Some assumptions about lateral collision risk were made for each portion. The first assumption concerns risk of lateral collision for aircraft during the first one-third of the oceanic crossing. As an aircraft enters the CEP over the inbound gateways it is still navigating on accurate short-range, land-based aids, if non-INS equipped. If INS-equipped the aircraft should be maintaining small cross-course errors because of the propinquity of the gateway to the departure airport, which is also usually the INS initialization point. It is thus unlikely that an aircraft would exhibit any large cross-course errors during the first part of the flight. Since the operational constraints of the existing CEP are such that aircraft assigned to the same flight level fly in the same direction, it is quite unlikely that the relative errors of an aircraft pair assigned to adjacent tracks would be such that they would lose all planned lateral separation in the first part of the crossing. Thus, it was assumed that there exists no lateral collision risk for westbound aircraft in the eastern portion of the track system, nor for eastbound aircraft in the western portion of the system.

It was assumed that the lateral collision risk was uniform throughout the central portion of the system and the same for both eastbound and westbound aircraft, and it was further assumed that the collision risk for westbound aircraft in the western portion and for eastbound aircraft in the eastern portion

of the original CEP was also uniform. By "uniform," it is meant that the lateral collision risk estimated from data taken in a given area of a portion is representative of the risk existent throughout the portion. This assumption would seem reasonable for the central portion, since the probability of lateral overlap was estimated from data taken in the middle of the portion. The assumption would seem conservative for the western and eastern portions, since data were taken as aircraft neared the end of their crossings where navigation errors may have been largest.

In order to calculate the lateral collision risk for the entire CEP track system, it was necessary to combine the estimates of risk for each of the portions. The method of combination chosen was to make the contribution of each portion to the overall lateral collision risk proportional to the percentage of total system flying time (the sum of the individual flying times of all flights in the system) for which lateral collision risk exists in that portion. Thus, for an eastbound aircraft flying at a constant speed, one-third of the flight's system flying time was spent in the western portion with no associated lateral collision risk, one-third in the central portion, with a lateral collision risk estimated for that portion, and one-third in the eastern portion, with an attendant risk of collision due to the loss of all planned lateral separation particular to that portion. Symmetry suggests the same scenario for a westbound flight.

For computational convenience, it was assumed the time to transit the original CEP in either direction at any flight level was the same. With this assumption, the contributions, or weights, of the lateral collision risks in each portion can be made proportional to the percentage of total system flights which are exposed to lateral collision risk in that portion. From table 5, it can be seen that eastbound flights constitute 47.2 percent of the total system traffic and westbound flights the remaining 52.8 percent. The weights, normalized such that their sum is 1.0, used to combine the lateral collision risks estimated for each portion of the original CEP are presented in table 19.

MONTE CARLO ESTIMATION OF LATERAL COLLISION RISK. Experience in the North Atlantic organized track system has shown that the lateral is the largest in magnitude of the collision risks, and the NAT/SPG has paid particular attention to the procedure for estimating this quantity. Realizing that risk model parameters estimated from data taken in the track system are central estimates and that embedded in the estimation process are possible inaccuracies due to sampling fluctuations and small sample sizes, the NAT/SPG developed a method of dealing with the variability associated with an estimate of lateral collision risk. Model parameters identified as those with estimates which are inherently variable were: (1) $P_y(S_y)$, the probability of lateral overlap, (2) E_y(same) and E_y(opp), the same and opposite-direction lateral occupancies, and (3) $|\dot{y}(S_y)|$, the relative crosstrack velocity of an aircraft pair which has lost all planned lateral separation. Lateral occupancy and relative crosstrack velocity were modeled as linear functions of average daily traffic count and separation lost, respectively. For each fit, the standard error of the slope was taken by the NAT/SPG as adequate to describe the variability associated with the estimate.

TABLE 19. FACTORS USED TO WEIGHT SYSTEM PORTION CONTRIBUTIONS TO OVERALL LATERAL COLLISION RISK FOR EXISTING CEP

(1) System Portion	(2) Direction of Flight	(3) Ratio of Total System Flight Time Spent in Portion	(4) Ratio of Total Traffic, Direction of Flight	(5) Weighting Factor ((3) x (4))	(6) Normalized Weight ((5)/0.666)
Western	Westbound	0.333	0.528	0.176	0.264
Central	Westbound	0.333	0.528	0.176	0.264
Central	Eastbound	0.333	0.472	0.157	0.236
Eastern	Eastbound	0.333	0.472	0.157	0.236
Total	-	-	-	0.666	1.000

The variability associated with the estimate of $P_y(S_y)$ was somewhat more difficult to prescribe. The probability of overlap is proportional to the self-convolution of the distribution of lateral deviation. The magnitude of the convolution is determined by both the frequency of flying errors at least as large as half the lateral separation standard and the shape of the tails of the lateral error distribution. The variability in the number of large flying errors was modeled by the NAT/SPG as a Poisson distribution with the characterizing parameter taken as the number of large flying errors observed during the data collection. The shape of the tail was taken to be between exponential and rectangular, or "level," in the terminology of the NAT/SPG, as has been discussed.

The effect upon the lateral collision risk of the variability inherent in the estimates of the three model parameters is determined via a Monte Carlo simulation. The simulation is performed by a FORTRAN program which accepts as inputs the statutory, concurred, and estimated risk parameters as well as the standard errors of the slopes of the occupancy and relative lateral velocity regression lines. The program replicates the calculation of lateral collision risk 1,000 times. At each replication, pseudorandom numbers generated by the program result in the selection of a sample of occupancy, relative lateral velocity, and number of large flying errors from the appropriate reference distributions. The number of large flying errors is used to compute a probability of lateral overlap, under each of the two-tail shape assumptions, which can be represented by $P_y(\text{level})$ and $P_y(\text{exponential})$. These are combined to form the $P_y(S_y)$ used in the calculation of risk at the current replication via $P_y(S_y) = r\ P_y(\text{level}) + (1-r)\ P_y(\text{exponential})$, where r is a pseudorandom number between 0.0 and 1.0. After the replications, the program orders the 1,000 values of estimated lateral collision risk by size and prints out the 500th and 900th largest. The 500th largest value, or 50-percent risk value as it is termed, is taken as the central estimate of lateral collision risk, while the 900th largest value, or 90-percent risk value, is regarded as a 90-percent confidence limit for the central estimate.

The NAT/SPG has utilized the Monte Carlo simulation results in two ways. In the first method, an estimate of lateral collision risk is calculated using the central estimates of all model parameters, with the value of $P_y(S_y)$ determined by the self-convolution of the lateral deviation distribution observed during data collection. The calculated collision risk is then multiplied by the ratio of the 90-percent risk value to the 50-percent risk value determined from the Monte Carlo simulation in order to produce the estimate of lateral collision risk for the system. The ratio, termed the "safety factor," is regarded as the increase in the central estimate of risk required to account for the variability in the estimates of the model parameters. In terms of the mathematical manipulations involved, the method may be expressed as:

$$\left\{\begin{array}{l}\text{estimate of}\\ \text{lateral collision}\\ \text{risk}\end{array}\right\} = \left\{\frac{\text{90\% Monte Carlo risk value}}{\text{50\% Monte Carlo risk value}}\right\} \times \left\{\begin{array}{l}\text{calculated}\\ \text{lateral risk using}\\ \text{central estimates}\\ \text{of parameters}\end{array}\right\}$$

As an alternative to this method, the NAT/SPG has used the 90-percent value of risk from the Monte Carlo simulation directly as the estimate of lateral collision risk in the track system. This second method has been employed when the 90-percent risk value and the estimate of collision risk involving multiplication by the safety factor have been considered to be close or when an extensive data collection designed to estimate the entire distrbution of lateral deviations has not been undertaken.

The estimates of lateral collision risk for both the existing and the proposed alternative composite CEP track systems are 90-percent risk values resulting from Monte Carlo simulations using the FORTRAN program employed by the NAT/SPG. These risk estimates are conservative relative to estimates based upon safety factor increases to central risk estimates, in the sense that the 90-percent values are larger. This conservative approach has been adopted in order that any changes in either model parameter estimation techniques or risk calculation methods may be compared to what may be termed a "worst-case" level of lateral collision risk computed under pessimistic lateral collision risk model assumptions. In particular, it has been determined through experimentation with the Monte Carlo simulation program that the 90-percent risk value is generally very close to the lateral collision risk which would result if the distribution of lateral deviations were to have a level tail. The lateral deviation data of figure 10 suggest that a level tail is not characteristic of observed CEP cross-course errors.

ESTIMATE OF LATERAL COLLISION RISK FOR THE EXISTING CEP TRACK SYSTEM. The lateral collision risk was determined separately for each of the three portions of the existing CEP as the 90-percent risk value resulting from Monte Carlo simulation. Concurred and estimated parameters with the same value for all portions were $\lambda_x = \lambda_y = 0.033$ nmi, $\lambda_z = 0.0085$ nmi, $P_z(0) = 0.25$, $|\dot{z}| = 1$ knot, $S_x = 120$ nmi, and $|\overline{\Delta V}| = 29$ knots. Inputs to the simulation program particular to the three portions are presented in table 20. The lateral collision risk estimated for the overall system was then computed as the weighted sum of the risks from each portion, using the weights of table 19. The estimated number of accidents in 10 million track system flying hours due to the loss of all planned lateral separation, N_{ay}, for the existing CEP presented as a function of average daily traffic count is shown in table 21 and displayed in figure 18.

ESTIMATE OF LONGITUDINAL COLLISION RISK FOR THE EXISTING CEP. The CEP study was directed toward a comparison of lateral collision risk for the existing system to the lateral and composite collision risks for proposed alternative structures. For completeness, an estimate of the longitudinal collision risk was also made. This estimate must be considered to be a rough one, since precise determination of parameter values for the longitudinal collision risk model would require a data collection at least as extensive as that described in this report, but oriented toward measuring the unexplained along-track separation loses of many thousand aircraft pairs initially spaced by no more than 60 minutes. Prior to any such data collection, the NAT/SPG longitudinal collision risk methodology would also have to be exposed to the same scrutiny as has the lateral in the past. That which is presented as the estimate of longitudinal collision risk for the CEP is that based upon parameters assigned values from the 1973-1974 data collection and calculated from NAT/SPG methodology developed to date.

TABLE 20. MONTE CARLO SIMULATION PROGRAM PARAMETERS USED IN CALCULATION OF LATERAL COLLISION RISK ESTIMATES FOR EXISTING CEP TRACK SYSTEM

Simulation Model Parameter	Western Portion	Central Portion	Eastern Portion North-Alfa Pair	Eastern Portion Alfa-Bravo Pair	Eastern Portion Bravo-South Pair
Sample size of Lateral Deviation Data	8,478	3,543	7,582	7,582	7,582
σ(nmi)	6.34	7.90	6.88	6.88	6.88
S_y(nmi)	100	100	100	150	100
Number of Navigation Errors at Least as Large as $S_y/2$	4	6	19	4	19
Same Direction Lateral Occupancy	0.00490	0.00490	0.00171	0.00248	0.00145
Slope Intercept	-0.12682	-0.12682	-0.05730	-0.00817	-0.08008
$\overline{\lvert \dot{Y}(S_y) \rvert}$ (knots)	53	53	53	71	53
Std. Error of Estimate	6	6	6	13	6
S_x(nmi)	120	120	120	120	120

TABLE 21. ESTIMATES OF LATERAL COLLISION RISK FOR EXISTING CEP SYSTEM

Average Number of Daily Flights	Estimate of Lateral Collision Risk, N_{ay}
80	0.261
90	0.314
100	0.366
130	0.525
184 (1985 est.)	0.814

The expression for N_{ax}, the expected number of accidents in 10 million track system flying hours due to the loss of planned longitudinal separation, is given by equation 4 in this report. Values for λ_x, λ_y, λ_z, $P_z(0)$, and $|\dot{z}|$ used in the calculation of N_{ax} were the same as used for the estimate of N_{ay}. The value of V was taken to be 480 knots. Using the distributions of lateral deviation shown in figure 10, $P_y(0)$ for the CEP was estimated to be 0.0033. The value of $|\dot{y}(0)|$ was obtained from figure 11. Because of previously mentioned factors, $|\overline{\Delta V}|$ was taken to be 29 knots from table 13.

It was determined under conservative assumptions (reference 8) that the maximum unexplained loss of along-track separation in the CEP would be approximately 17 minutes; that is, that $P_x(t)$ should be 0.0 for a t of 18 minutes or more. This finding agrees with the data of figure 17. It was then assumed that $E_x(t)$ was a constant value ($E_x(17)$ from table 16) for all t at least as large as 15 minutes and zero otherwise, a conservative assumption. Thus, the estimate of $\Sigma E_x(t)P_x(t)$ became $E_x(17)\ \Sigma P_x(t)$ for t at least as large as 15 minutes). From figure 17, $\Sigma P_x(t)$ is approximately 0.0021. As a result, N_{ax} was roughly estimated as 0.17 accidents in 10 million flying hours.

ESTIMATE OF VERTICAL COLLISION RISK FOR THE EXISTING CEP TRACK SYSTEM. The NAT/SPG was unable to directly estimate the vertical collision risk for aircraft with 2,000 feet planned vertical separation. Rather, since experts within the group decided that the risk was indeed very small relative to the lateral, the NAT/SPG concurred on a value of 0.02 accidents in 10 million flying hours. No new information concerning vertical position keeping or collision risk has come to light since those original deliberations, and thus the estimated value of vertical collision risk in the existing CEP was taken to be that concurred for the NAT, with one exception. Whatever the true value of the vertical collision risk, it is certainly proportional to the probability of lateral overlap of two aircraft assigned to the same route, $P_y(0)$. Because lateral path keeping had improved since the original NAT deliberations concerning vertical collision risk in 1968 (reference 7), it seemed appropriate to take the improvement into account in the specification of a vertical collision risk for the CEP. The NAT-estimated value for $P_y(0)$ in 1968 was 0.0012. Using the data of figure 9, $P_y(0)$ for the existing CEP was estimated to be 0.0034. The ratio of $P_y(0)$ in the existing CEP to $P_y(0)$ in the 1968 NAT is thus 2.83. Multiplying the 1968 NAT-concurred value for the vertical collision risk by this ratio provides the estimate of the risk of collision due to the loss of all planned vertical separation in the existing CEP: 0.06 accidents in 10 million flying hours.

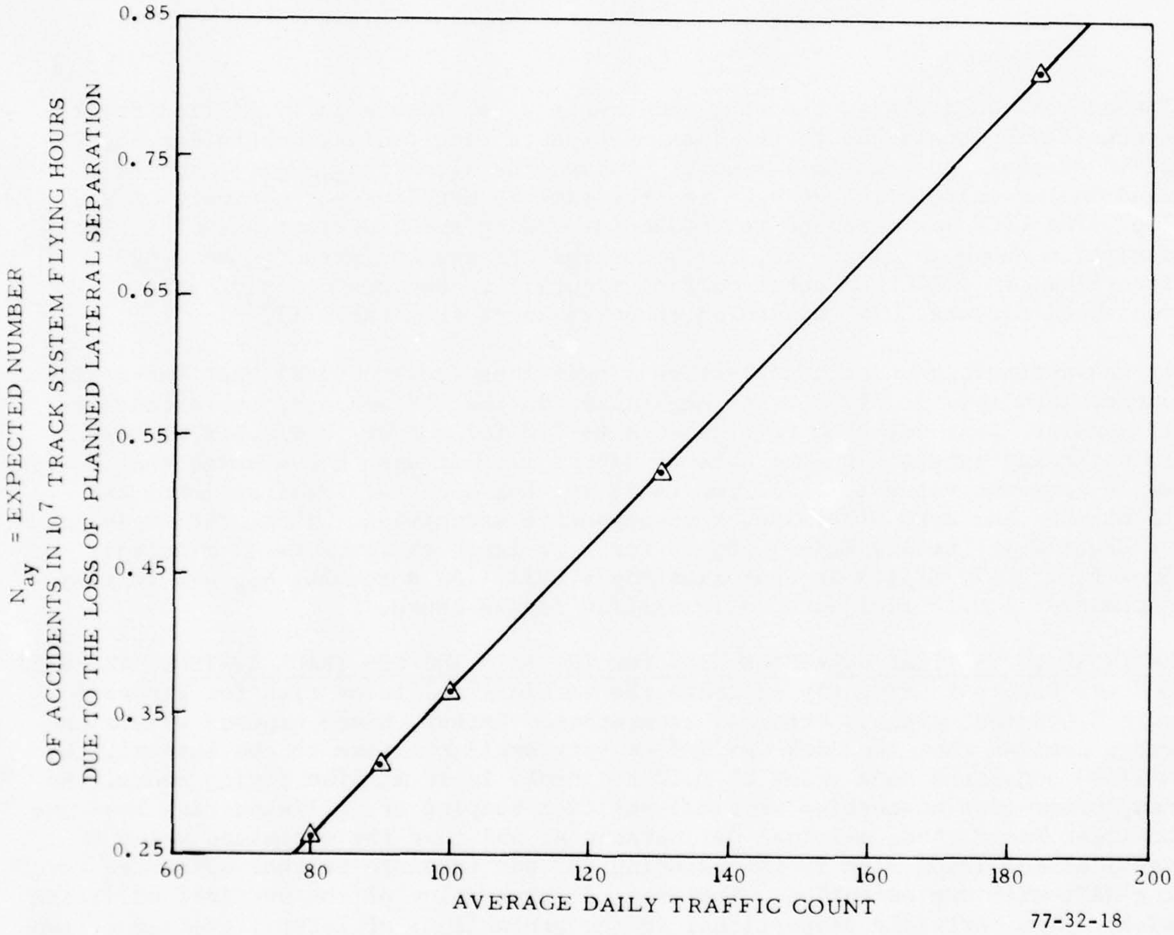

FIGURE 18. N_{ay} AS A FUNCTION OF AVERAGE DAILY TRAFFIC COUNT FOR THE EXISTING CEP TRACK SYSTEM

COLLISION RISK ESTIMATES FOR THE PROPOSED COMPOSITE CEP TRACK SYSTEM.

In order to determine a suitable composite system replacement for the existing CEP track structure, several alternative configurations were studied. After all candidate systems were thoroughly defined in terms of geographic coordinates, lateral and composite separations, and available flight levels of the routes involved, an estimated collision risk and expected annual fuel consumption were calculated for each alternative. The composite track system chosen from among the alternatives was shown in figure 5. Each of six routes (called R64, R65, R66, R74, R75, and R76) is a composite route with respect to its laterally adjacent neighbors, as is indicated in the flight levels available by route in table 22. As with the existing CEP, the direction of flight within a route alternates by successive flight levels. Since simulation predicted that the two most heavily traveled routes would be R65 and R75, which are composites to each other, the lateral occupancy of the composite system was expected to be greatly reduced from that in the existing CEP track structure. Lateral separation between routes with the same available altitudes remains as it is in the existing CEP for the western and central portions, but is increased in the eastern portion. Users of the proposed composite CEP would be presented with a set of available flight level and route combinations which is much more favorable from a fuel economy standpoint than is that in the existing CEP system.

TABLE 22. COMPOSITE CEP TRACK SYSTEM ROUTES AND AVAILABLE FLIGHT LEVELS

Route	Connecting Cities	Available Flight Levels	Eastern Gateway	Western Gateway
R64	SFO-HNL	Set 1	LEAFS	NEPTO
R65	SFO-HNL	Set 2	BIRCH	RIGER
R66	SFO-HNL	Set 1	FRUIT	AGATE
R74	LAX-HNL	Set 2	CERES	VOLLY
R75	LAX-HNL	Set 1	WILOW	GYPSY
R76	LAX-HNL	Set 2	YUCAN	YULES

Note: Set 1 = flight levels 290, 310, 330, 350, 370, 390, 410
Set 2 = flight levels 300, 320, 340, 360, 380, 400

The estimation of collision risk for the proposed composite CEP track system was based upon data gathered in the existing CEP and projections from the simulation program. A basic assumption in the calculation of collision risk estimates for the composite system was that navigation performance, as observed during the data collection program, would remain unchanged if the CEP were reconfigured. Under this assumption, the principal impact of a composite system upon lateral and longitudinal collision risk was the need to reestimate aircraft proximities. An estimation of composite collision risk completed the safety analysis of the composite CEP track system.

Occupancy estimates required in the calculation of the lateral, longitudinal, and composite collision risk of the composite CEP structure were obtained using information generated by the track system simulation program. As part of the program output, data in a form similar to that obtained from ATC facilities in the existing CEP system were assembled. From this data, lateral same-direction occupancies, composite same- and opposite-direction occupancies (estimates of the proportion of time that aircraft were separated laterally by 1/2 S_y, vertically by 1/2 S_z, and within S_x of each other), and the proportion of aircraft pairs with various initial longitudinal separations were estimated.

ESTIMATE OF LATERAL COLLISION RISK FOR THE PROPOSED COMPOSITE CEP TRACK SYSTEM. As was the case with the existing CEP structure, the lateral collision risk estimated for the composite system was calculated as a weighted sum of the risks in the eastern, central, and western portions. The lateral collision risk estimated for each portion was taken as the 90-percent risk value produced by the NAT/SPG Monte Carlo simulation program exercised with input data descriptive of navigation performance and occupancies for that portion.

Navigation performance in the composite CEP was taken to be that observed in the existing CEP during the data collection program. Thus, any differences between values of the navigation-related risk model parameters $P_y(S_y)$ and $|\overline{\dot{y}(S_y)}|$ in the composite and existing CEP systems resulted from changes in separation standards in the three portions under the composite structure. Since the adoption of a composite structure would result in no change in along-track relative speed, $|\overline{\Delta V}|$ was the same in composite system lateral collision risk calculations. However, the new route definitions and flight levels resulted in planned lateral separations in the proposed composite which are quite different from those in the existing CEP structure as is shown in table 23.

TABLE 23. LATERAL SEPARATION OF PROPOSED COMPOSITE SYSTEM ROUTES

	Lateral Separation Standard (nmi)		
Route Pair	Eastern Portion	Central Portion	Western Portion
R64-R66	100	100	100
R65-R74	215	160	110
R66-R75	215	160	100
R74-R76	100	100	100

Estimation of lateral same-direction occupancies for the route pairs of table 23 was done by fitting regression lines to sample occupancies calculated from the track system simulation program output for various values of simulated average daily traffic count. Analysis of the estimates indicated that there was essentially no lateral occupancy for the R64-R66 route pair and that lateral

occupancies for the remaining route pairs were generally one-half the magnitude of occupancies estimated for the former CEP system. The increased lateral separation between composite system route pairs in the eastern and central portions, when compared to the separations of the existing CEP, resulted in smaller values of $P_y(S_y)$. The compound effect of reduced occupancy and smaller probability of lateral overlap produced a considerably smaller estimate of lateral collision risk for the composite CEP system. Table 24 presents, as a function of average daily traffic count, the risk of collision due to the loss of all planned lateral separation estimated for the proposed composite CEP track system. Figure 19 displays the estimates of table 23.

TABLE 24. ESTIMATED LATERAL COLLISION RISK FOR PROPOSED COMPOSITE CEP SYSTEM

Average Number of Daily Flights	Estimated Lateral Collision Risk, N_{ay}
80	0.081
90	0.090
100	0.100
130	0.127
184 (1985 est.)	0.176

ESTIMATE OF RISK OF COLLISION DUE TO LOSS OF COMPOSITE SEPARATION FOR THE PROPOSED COMPOSITE CEP TRACK SYSTEM. The calculation of the risk of collision due to the loss of composite separation was discussed at the Fifth Meeting of the NAT/SPG (reference 7). The question commanding most attention during the deliberations was the proper estimation of $P_z(1000)$, the probability that an aircraft pair with planned vertical separation 1,000 feet would lose all separation. Lacking adequate data to directly estimate the quantity, the NAT/SPG decided to convolve existent distributions of known sources of vertical-position-keeping error in order to estimate values for $P_z(1000)$, under the assumption that independent contributions by these error sources alone would give rise to the loss of 1,000 feet planned altitude separation. As a result of the mathematical development, the NAT/SPG calculated the probability of vertical overlap for 1,000 feet planned separation from

$$P_z(1000) = 0.000012 + 0.039042tR + 0.002626t^2R^2$$

where R and t are parameters of the altimeter static calibration error distribution, R being the failure rate and t the time interval in years between static calibration checks. Making use of the conservative estimates for R and t made by the NAT/SPG, the estimate of $P_z(1000)$ for the CEP is 0.0012.

The lateral separation between composite routes was taken to be 50 nmi in order to simplify composite collision risk calculations. One exception to this standardized separation was made in the eastern portion of the track system. Due to the large lateral separation between R65 and R76, it was

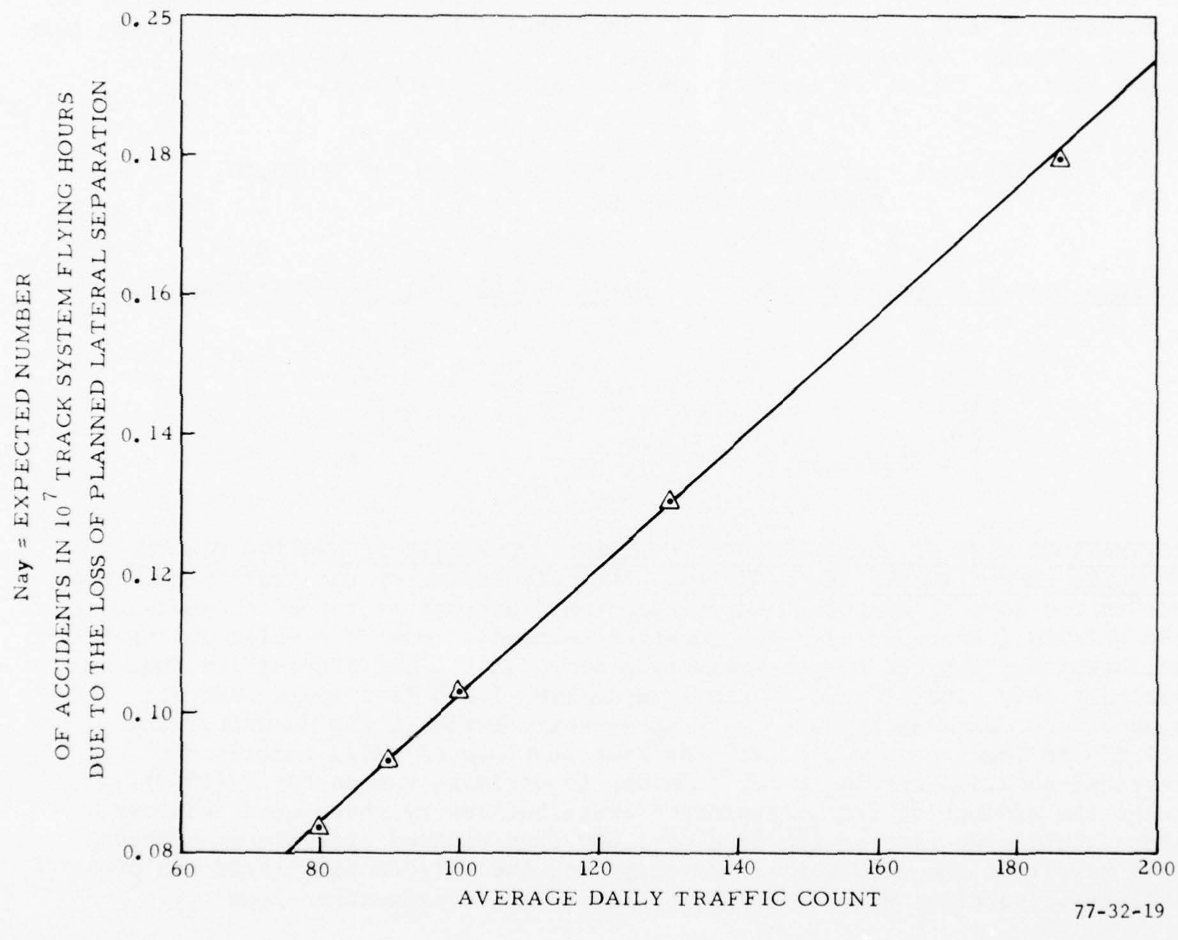

FIGURE 19. N_{ay} AS A FUNCTION OF AVERAGE DAILY TRAFFIC COUNT FOR THE PROPOSED COMPOSITE CEP TRACK SYSTEM

assumed that no risk of collision due to the loss of composite separation existed between these routes in this area. The probability of lateral overlap required for composite collision risk calculations, $P_y(50)$, was estimated from the data of figure 10 to be 1.52×10^{-6}. Since the composite collision risk in the composite CEP was found to be at least an order of magnitude less than the lateral during preliminary analysis, the complexity of a weighted calculation of collision risk was eschewed in the composite case.

Unlike the lateral collision risk case, the structure of the proposed composite CEP track system generated opposite as well as same-direction composite occupancies. The same and opposite-direction composite occupancies determined from regression line fits to track system simulation program output data are presented as a function of average daily traffic count in table 25. The constant value for opposite-direction occupancy represents a conservative value chosen from among the track system simulation program occupancies. The simulated occupancies failed to follow an increasing trend as a function of increasing average daily traffic count, a result similar to that observed for opposite-direction lateral occupancy in the North Atlantic.

TABLE 25. ESTIMATES OF SAME- AND OPPOSITE-DIRECTION COMPOSITE OCCUPANCY FOR PROPOSED COMPOSITE CEP SYSTEM

Average Number	Composite Occupancies	
of Daily Flights	Same-direction	Opposite-direction
80	0.091	0.027
90	0.102	0.027
100	0.112	0.027
130	0.143	0.027
184	0.198	0.027

The risk of collision due to the loss of composite separation in the proposed composite CEP is presented as a function of average daily traffic count in table 26. It can be seen from comparison with table 24 that the additional collision risk estimated to be introduced into the CEP because of composite separation would be negligible in comparison to the estimated lateral collision risk.

ESTIMATE OF LONGITUDINAL COLLISION RISK FOR THE PROPOSED COMPOSITE CEP TRACK SYSTEM. As with the lateral and composite cases, the track system simulation program output was used to generate aircraft pair proximities required by the longitudinal collision risk model. These proximities, the distribution of initial along-track spacing for aircraft pairs, led to a calculation of the estimated risk of collision due to the loss of all initial longitudinal separation in the composite CEP of 0.13 accidents expected in 10 million track system flying hours.

TABLE 26. ESTIMATE OF RISK OF COLLISION DUE TO THE LOSS OF COMPOSITE SEPARATION IN THE PROPOSED COMPOSITE CEP SYSTEM

Average Number of Daily Flights	Expected Number of Accidents in 10 Million Flying Hours
80	0.0025
90	0.0026
100	0.0026
130	0.0028
184 (1985 est.)	0.0031

ESTIMATE OF VERTICAL COLLISION RISK FOR THE PROPOSED COMPOSITE CEP TRACK SYSTEM. The introduction of composite separation into the CEP track system should not have any adverse effect upon vertical collision risk. In fact, the vertical collision risk in the proposed composite CEP structure might well be lower than that in the existing system, since the dispersal of aircraft among six routes instead of four may well reduce vertical occupancy. Lacking sufficient data to adequately estimate safety in the vertical domain, the risk of collision due to the loss of all planned vertical separation in the proposed composite CEP system is estimated to be that for the existing track structure, namely, 0.06 accidents expected in 10 million track system flying hours.

COMPARISON OF COLLISION RISK IN THE EXISTING AND THE PROPOSED COMPOSITE CEP TRACK SYSTEMS.

The increase in safety, as measured by estimates of lateral collision risk, produced by the introduction of composite separation into the CEP track system would appear to be considerable. Drawing upon the contents of tables 21 and 24, figure 20 presents a comparison of the lateral collision risks estimated for the existing and the proposed composite CEP structures. Of particular interest in the figure is the fact that the lateral collision risk estimated for the proposed composite CEP under forecasted 1985 traffic loadings is 53 percent of the lateral collision risk estimated for the existing system at at a daily count of 93 flights, the overall average observed during data collection. Thus, there would be room for substantial traffic growth in the composite system before lateral collision risk levels approximating those estimated to exist in early 1974 would be encountered. The price paid for the introduction of additional routes and composite separation in terms of additional collision risk due to the loss of composite separation would be relatively small. Comparison of the expected number of accidents presented in tables 24 and 26 show that the risk of collision due to the loss of composite separation is at least an order of magnitude smaller than the risk of collision due to the loss of lateral separation. In addition, at corresponding traffic levels, the sum of the lateral and composite collision risks in the proposed composite system is well below the lateral collision risk estimated for the existing system.

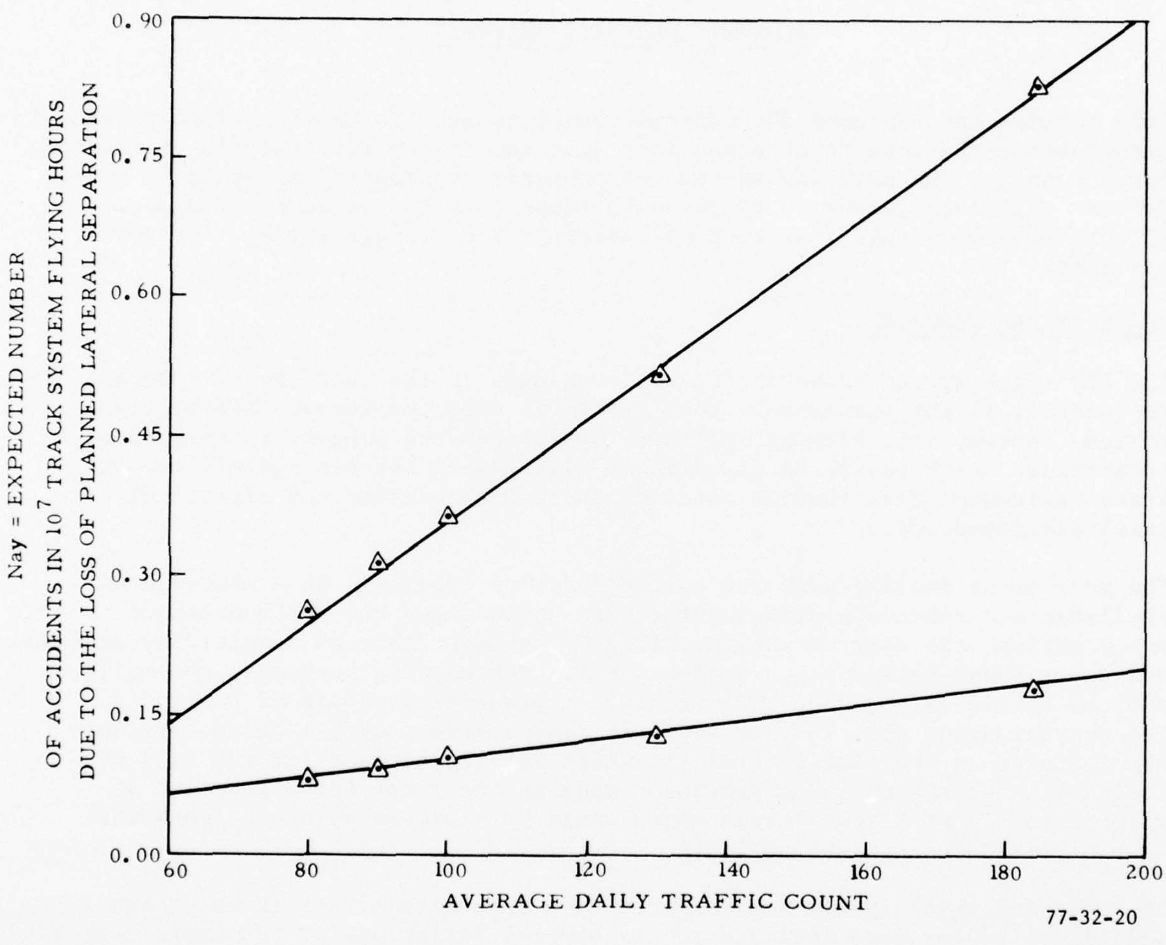

FIGURE 20. N_{ay} AS A FUNCTION OF AVERAGE DAILY TRAFFIC COUNT FOR THE EXISTING AND PROPOSED COMPOSITE CEP TRACK SYSTEMS

Based upon track system simulation program data, the introduction of composite separation into the CEP would also serve to reduce the estimated risk due to the loss of all initial along-track separation. Comparison of the existing system with the proposed shows a reduction in longitudinal collision risk of approximately 24 percent. As has been stated, no change in vertical collision risk resulting from the introduction of composite separation into the CEP track system can be estimated.

ECONOMIC BENEFITS ANALYSIS

This section expands upon the economic benefits methodology described previously and presents the results obtained from an economic benefit analysis of the CEP track system. The existing system was compared to proposed alternative track systems utilizing composite routes with respect to two measures of system effectiveness: average fuel burn per aircraft and average flying time per aircraft.

TRACK SYSTEM GEOMETRY.

The CEP track system shown in figure 3 was used in the cost analysis model. In general, flight planning in this system is directed towards minimization of fuel consumption, although military operations are subject to additional constraints which result in significant differences between the minimum-fuel track assignment distribution obtained through simulation and historical track assignment data.

The problem of dealing with the multiplicity of terminals in a manner both realistic and tractable arises a fortiori in modeling the North Atlantic track system. In that situation, NAT/SPG concluded through sensitivity analyses and upper bound estimation procedures that, for costing purposes, the multiplicity of terminals could be replaced by a representative pair of terminals. The approximation used in this study is less severe, because three terminals are included in the model, terminals which in fact account for the bulk of traffic in the system. The provision made in the model for a fraction of flights to fly at flight levels which would be achieved by overflights was also utilized in the cost analysis.

The existing track system was compared to a composite system in which two additional routes were included and to several variations of the basic composite system. The composite system first studied included the four existing routes and two composite routes, Yankee (between Bravo and South) and Victor (between Alfa and North), indicated by dashed lines in figure 4. Even flight levels, which are not utilized in the present system, were used on the composite routes so that aircraft flying these two additional routes would be separated from aircraft on present routes vertically by 1,000 feet and laterally by half the present lateral separation. Two systems of route directionalities known as "composite-above" and "composite-below" were studied to ascertain relative merits of each as compared to the present system. The configurations of the

composite system with these directionalities are shown in figure 21. In the composite-above configuration, traffic in a given direction utilize flight levels 1,000 feet higher on the composite route than is dictated by the present altitude assignment scheme, and in composite-below, traffic utilizes the levels 1,000 feet below. The composite routes retain the rule of alternating directions for vertically adjacent paths on a given route.

An important simplification implicit in the modeling procedure was the neglect of benefits derived from the ability of system users to make enroute altitude and/or route changes, or, conversely, the penalties incurred when requests for such changes are denied. Data collated from all flight crew survey forms submitted during the month of April 1974 were examined to estimate the magnitude of this penalty.

Number of Logs	Number of Aircraft Assigned Paths Other than Filed	Enroute Requested	Changes Approved
1,591	148	33	23

These data show that during the month of April 1974, almost 10 percent of the aircraft using the CEP track system suffered penalties because they were assigned a track other than the track for which they filed, while only 10 aircraft out of 1,591, or 0.6 percent of the aircraft, were penalized through denial of an enroute track change request. Although the magnitude of an individual penalty resulting from denial of an enroute request is unknown, the rarity of their occurrence is sufficient justification for their exclusion from the analysis. NAT/SPG, in fact, made no attempt to include such penalties in the North Atlantic cost analysis. Freedom to change flight levels or tracks enroute, though not explicity evaluated in terms of a dollar cost in the present analysis, is nevertheless an intangible factor which enters into the judgment of individuals in reaching a final decision on which track system is most preferable.

COST ESTIMATION.

In the NAT/SPG study, the estimate of the cost penalty incurred due to the assignment of an aircraft to a nonoptimal track is expressed in three levels, known as the "low," "mid," and "high" cost estimates. The low estimate reflects the increase in direct operating cost resulting from an increase in flight time for aircraft assigned to nonoptimal tracks. The mid estimate includes, in addition, the carry cost of the additional fuel reserve required for each aircraft, because the average flight time is lengthened. The high estimate consists of the mid estimate plus the cost to airlines of revenue lost through the reduction of payload capacity due to increased fuel reserves.

Information provided by the airlines strongly indicates that the most signicant factor influencing choice of tracks is the expected fuel burn for the flight. United Airlines, in fact, carefully examined the question of the possible influence on overall operating cost of small positive or negative increments in mean flying time on a given route system. The conclusion

Composite Above — ROUTE

FLIGHT LEVEL	South	Yankee	Bravo	Alfa	Victor	North
410	E		E	E		E
400		W			W	
390	W		W	W		W
380		E			E	
370	E		E	E		E
360		W			W	
350	W		W	W		W
340		E			E	
330	E		E	E		E
320		W			W	
310	W		W	W		W
300		E			E	
290	E		E	E		E

Composite Below — ROUTE

FLIGHT LEVEL	South	Yankee	Bravo	Alfa	Victor	North
410	E		E	E		E
400		E			E	
390	W		W	W		W
380		W			W	
370	E		E	E		E
360		E			E	
350	W		W	W		W
340		W			W	
330	E		E	E		E
320		E			E	
310	W		W	W		W
300		W			W	
290	E		E	E		E

E = Eastbound W = Westbound

FIGURE 21. COMPOSITE TRACK SYSTEM CROSS-SECTION

reached was that no real differences in operating cost could be attributed to these flying time increments, since maintenance costs and scheduled maintenance are a function of cycles (number of takeoffs and landings) rather than flying time. Therefore, flight planning in the CEP (as elsewhere) is based solely on fuel burn considerations. Furthermore, neither fuel reserves nor payload capacity would be, in their opinion, changed in any measurable way by an incremental modification of the track system, so that they recommended exclusion of "mid" and "high" costing procedures from the analysis. Although some of the above conclusions may not apply in the case of unscheduled or charter operations, the scheduled carriers do constitute the bulk of commercial traffic in the CEP region. In addition, the military stated that since their mission and costing procedures were so different from the commercial operators, they were more interested in an analysis of fuel burnout and flight time individually. Therefore, the above recommendations were adopted.

It is appropriate to remark that in this analysis, differences in operating cost per aircraft from one track system to another are evaluated solely on the basis of differences in the distributions of oceanic paths assigned to entering aircraft, neglecting any possible changes in the magnitude or frequency of terminal area air traffic control delays or ground delays which might accompany a modification of the track structure. Ground delays, in particular, may be a significant factor, but both the analytical tools and the data requisite to the incorporation of such phenomena into the model are lacking.

Returning to a description of the flight planning data, four main assumptions which were made are again enumerated:

(1) Aircraft reach cruise altitude at or prior to the gateway.

(2) There are no route or altitude changes enroute.

(3) Aircraft operate at constant speed between gateways.

(4) Aircraft, with the exception of KC135, fly at constant mach number; the KC135 operates at a constant true airspeed of 450 knots regardless of altitude.

As previously mentioned, these assumptions are similar to those of the NAT/SPG investigations.

Additional detail beyond that in the NAT/SPG work was achieved by exercising the capability of the model to accommodate a multiplicity of aircraft types. Wide-bodied jets considered consisted of B747's and DC10's, and narrow-bodied jets included were DC8's, B707's, and B720's, for the commercial operators. The military widebody, the C5A, and the KC135 and C141 were also considered for a total of eight aircraft types.

A data collection effort was undertaken to obtain flight plan data for the desired aircraft types. Standard payloads were assumed, and fuel loading was based on expected fuel burn plus standard reserves for the best (minimum

fuel) path in the system, according to the standard flight planning procedure. Fuel burn and flight times for commercial aircraft for alternate paths were based on gross takeoff weights for the planned best path. For military operations the penalties were calculated assuming the flight was planned for the actual path eventually flown.

In calculating the flight plans, standard terminal-to-gateway and gateway-to terminal ascent and descent procedures were also assumed, including climb rate and choice of waypoints, with no delays or modifications due to air traffic control. This was a simplifying assumption, particularly in the case of Yankee route. Some of the users expressed concern about the usefulness of this route, due to military operations in the Long Beach area which might cause flights to be diverted and, hence, increase flying distances.

Another instance in which some aggregate characterization was required for a multiplicity of possible conditions arose in assessing the consequences of weather variability. Two alternative weather environments were considered, as indicated earlier, and the following simulation inputs were compiled separately for the winter season (defined as October 27 to April 30) and for the summer (defined as the remainder of the year): (1) fuel burnouts and flying times, (2) hourly traffic profiles, (3) fleet mix, and (4) daily traffic histogram.

DEMAND ON THE SYSTEM.

The previous section outlined the procedure to ascertain the operating cost for an individual flight in the CEP track system for the purpose of determining the relative costs of various possible route or flight level assignments. In order to determine the total operating cost associated with a given track system, it is necessary in addition to know the volume of air traffic for each aircraft type utilizing the system and the distribution of that traffic during the hours of the day.

The data required to develop all the air traffic spatial and temporal distributions discussed below were gathered by NAFEC during the CEP data collection program in 1973-74. For purposes of the cost analysis, data on 17,977 flights spanning the period from December 15, 1973, to June 30, 1974, were compiled. This file consisted of 12,344 flights from December 15, 1973, to April 30, 1974 (winter season), and 5,633 from May 1, 1974, to June 30, 1974 (summer season). Clearly this constitutes a sample from each season, rather than a representation of either season in its entirety, but the results of the analysis will demonstrate the adequacy of this data set.

Not only does the total cost increase as the volume of air traffic increases, but the average cost per aircraft increases as well, because it becomes more probable that an aircraft entering the system will find the most desirable paths occupied by other aircraft. This likelihood of incurring a larger cost (assignment of less desirable paths) is greatest during the peak traffic hours of the day, demonstrating the importance of modeling peak hour conditions with the greatest accuracy. Therefore, the demand on the system was modeled on an hourly basis. The peak instantaneous traffic in the model arises as a result

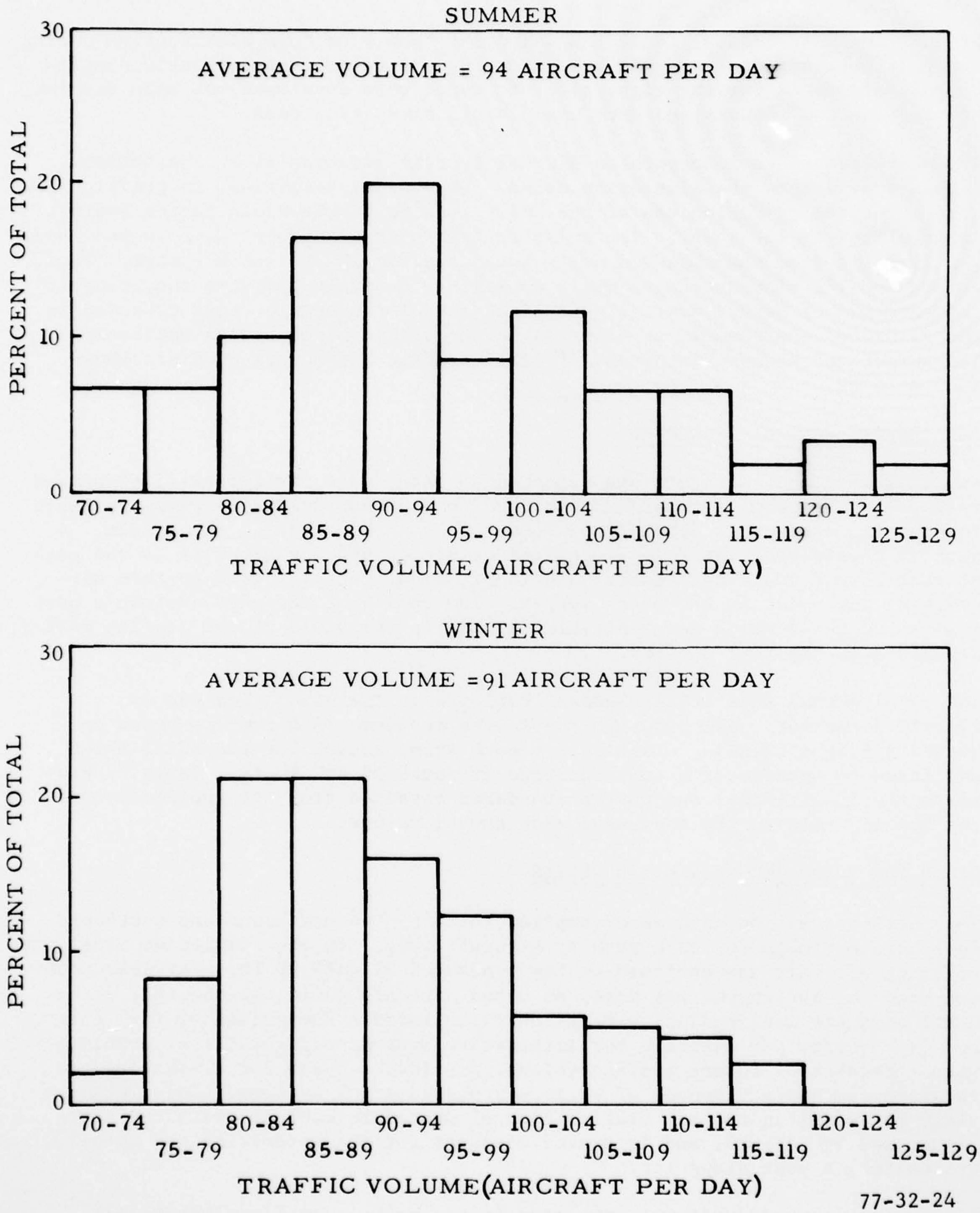

FIGURE 22. SUMMER AND WINTER DAILY TRAFFIC HISTOGRAMS

of the random process of generating aircraft from a uniform distribution during the peak hour and may vary slightly from the historical data. Hourly distributions of demand for the eight aircraft types were developed for each terminal and for the two seasons and were used in all simulation runs.

The above procedure incorporates diurnal traffic patterns (i.e., variations within a day) into the simulation model. Day-to-day variations in traffic flow were generated by making use of the daily traffic volume scale factor feature incorporated in the model. The daily traffic histogram input data to the model was compiled from the observed daily total traffic in the track system. Thus, during the 182 simulated days which constitute a single computer run, roughly the same mix of heavy, average, and light demand-for-service days occurred in the simulated environment as occurred in the actual track system environment. The summer and winter histograms of daily traffic which were used are shown in figure 22.

AIR TRAFFIC CONTROL PROCEDURE.

It is assumed that aircraft are assigned to paths on a first-come-first-served basis, and that each aircraft is assigned to the most desirable path available for the given aircraft type at the moment the aircraft enters the system. A path is considered available if assignment of an entering aircraft to the path at that moment would not result in a longitudinal conflict with another aircraft at any point in the track system. The choice of the most desirable path from among those which are available is made on the basis of the costing method described in the next section.

The longitudinal separation standard employed in the simulation was as described earlier. All aircraft types were assigned mach numbers based on standard flight planning practice for each type, except for the KC135 which was taken to operate at a constant true airspeed of 450 knots. Table 27 displays the longitudinal separation standards obtained from the application of the spacing rule to the indicated mach number values.

BASIS FOR COMPUTING ECONOMIC BENEFITS.

The fuel consumption data were compiled to obtain an eastbound and westbound fuel burn estimate for each path by aircraft type. In the simulation model, the entering aircraft was assigned to the minimum-fuel path of the available paths, and once the assignment was made, no other aircraft could receive that path until adequate longitudinal separation was assured. Comparison of fuel burn and flying time per aircraft for alternative system configurations, combined with forecasts of future traffic volume, provided a basis for evaluating the relative cost-effectiveness of various proposed track systems. This methodology for modeling the air traffic control procedure conforms with the technique used by NAT/SPG, and it proved adequate for characterizing the actual system from a cost viewpoint.

Flying time per aircraft was tabulated in two ways. The first was merely summing the flight time for each flight. A second method was employed in which, if an aircraft arrived ahead of schedule, the scheduled time for the

TABLE 27. OCEANIC CRUISE SPEEDS AND ROUTE ENTRY SEPARATION STANDARDS

SEPARATION STANDARDS IN MINUTES

Speed (Mach)	Following Aircraft Type	B747	DC10	B720	B707	DC8	KC135	C5A	C141
		Leading Aircraft Type							
.84	B747	15	17.5	20	22.5	25	30	32.5	40
.83	DC10	15	15	17.5	20	22.5	27.5	30	37.5
.82	B720	15	15	15	17.5	20	25	27.5	35
.81	B707	15	15	15	15	17.5	22.5	25	32.5
.80	DC8	15	15	15	15	15	20	22.5	30
450 Knots TAS	KC135	15	15	15	15	15	15	17.5	25
.77	C5A	15	15	15	15	15	15	15	22.5
.74	C141	15	15	15	15	15	15	15	15

flight was tabulated as the flight time. This resulted as an outgrowth of discussions with United Airlines in which it was indicated that there is no apparent cost benefit to arriving ahead of schedule, while there is a definite penalty to arriving late. The justification of a penalty for late arrival and not a bonus for early arrival is that customer dissatisfaction and extra crew costs can be incurred by a late arrival, whereas crew costs are not affected by an early arrival, and it is felt that there is no appreciable additional passenger good will generated by being early rather than on schedule.

FLIGHT PENALTY CALCULATION.

Flight penalty calculations for fuel burn and flight time were performed using the flight plan information gathered in the data collection effort. In addition, charts showing the effect of gross weight on fuel burn were used to assist in developing the carry cost of fuel. It was assumed for Yankee route that aircraft could be transitioned from the eastern gate through the edge of the military zone.

For commercial aircraft, using the flight plan information and factors representing the carry cost of fuel, the fuel burn and flight time for each route were developed for an aircraft which had planned to fly the best track. Interpolation was performed to obtain values for the even flight levels used in the composite systems. Flight times and fuel burn for the C5A and C141 were provided for all eight routes along with a fuel burn chart. The calculations were performed assuming the maintenance of normal cruise speed at constant altitudes, using a fuel reserve sufficient to fly 10 percent of the enroute time plus fuel to reach an alternate terminal, Hilo (General Lymon) on Westbound missions and an airfield 100 nmi from destination on Eastbound. Flight plan calculations for the KC135 were performed for constant true air

speed (TAS) of 450 knots, using a 16-knot westerly wind factor for summer calculations and 40-knot wind westerly factor for winter. Flight times were provided for North, Alfa, Bravo, South and two composite routes, Uniform (north of North) and Zulu (south of South), which were initially under consideration. Hourly fuel burn as a function of altitude and during climb and descent was also provided.

It was indicated during the data collection effort that, due to the navigational equipment in use, if a KC135 were denied its initial track request, it would opt for a lower flight level on the requested route and attempt to obtain the preferred altitude clearance enroute, rather than plan for another route. Route preferences for the KC135 were developed on this basis rather than selecting the next least costly path, as was done for all other types of aircraft.

The military indicated that they normally received the path requested, because they knew in advance which paths were likely to be crowded and planned accordingly. Frequently, they also deliberately filed for North or South routes with the expectation of receiving step climbs enroute, which made the use of these routes more economical than flying constant altitude on Alfa or Bravo where step climbs were more often denied. Because of this, the fuel burn of military aircraft for each route was calculated assuming that the aircraft had planned to fly the route. Again interpolation was performed to obtain values for the even flight levels of the composite structure. The simulation was structured to consider five path preferences for each of the eight aircraft types.

SIMULATION PROGRAM.

In the analysis, each simulation run consists of 182 simulated days. For output purposes, data were gathered in weekly increments so that results for each run were tabulated for 26 weekly periods. Each of the runs were identified by season (summer/winter), track system structure (present/composite above/composite below) and traffic level (100, 110, 120, 130, and 196 percent of present level--the 196 percent representing a 1985 forecast of traffic.) Traffic level was generated by applying an overall traffic volume scale factor to the histogram of hourly traffic developed from the historical data.

Overflights, lightly loaded aircraft which would fly higher than normally expected, and other unidentified factors that would give rise to the selection of routes and flight levels different from those predicted based upon standard aircraft performance profiles were simulated using the feature which allowed specifying a given percentage of aircraft to be assigned a flight level other than normally expected.

At the end of each simulated week, cumulative statistics for the quantities of interest were printed. Weekly outputs of the simulation included route and flight level availability by aircraft type, total fuel burn and flight time for each terminal and totaled over all terminals, opposite-direction

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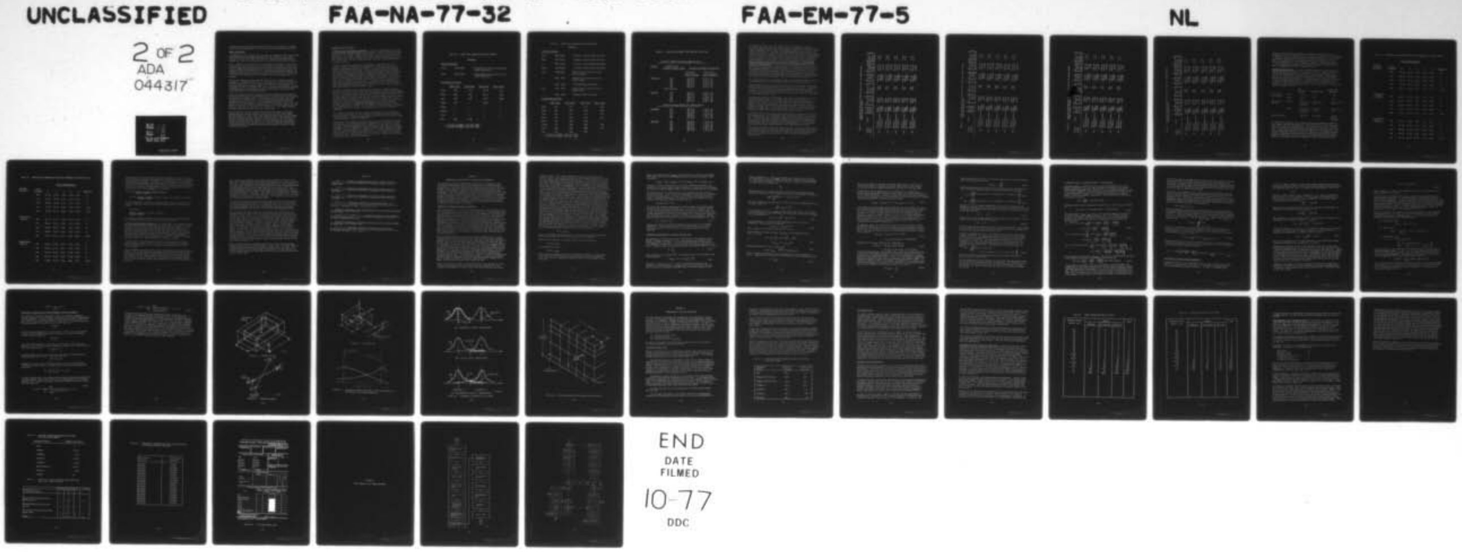

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proximity counts, same-direction proximity counts, and a data slice crossing time interval histogram which could be used to derive longitudinal proximity.

MODEL VERIFICATION.

Preliminary runs of 60 days traffic were made for purposes of model verification. Runs were made for both summer and winter weather conditions with a daily average of 94 and 91 aircraft, respectively. Several interesting features emerged as a result of the comparison of the simulated and historical results.

First, a number of aircraft in the actual system were assigned to paths nominally barred to them according to the directional restrictions. Out of 5,304 aircraft comprising the historical sample, 102 were on these paths, with 88 of those occurring for eastbound traffic. Although this phenomenon suggests the existence of some informal protocol for track exchanges between eastbound and westbound controllers, such a protocol would fall outside of the official definition of the track structure, and therefore was not incorporated into the analysis.

Second, the simulation results indicated that aircraft in general, sought assignment to the highest flight level consistent with climb rate restrictions and other constraints. This is simply a consequence of the fact that fuel burn decreases with increasing flight level. The greater diffuseness of track assignments in the actual rather than in the simulated system probably resulted from overflights and variations in payload and/or weather conditions which caused variations in the maximum altitude.

Third, the simulation results suggested and the fuel burn data confirmed the fact that aircraft which do not receive their most desirable path in the system should choose to change routes at the preferred altitude rather than change altitudes on the preferred route. The historical data indicated that the opposite had been the practice. This is perplexing because the fuel data indicate that a route change at altitude should be preferred, usually by a wide margin, so that one is led to conclude either that fuel burn alone was not the sole cost criterion for path selection in practice, or that flight planning involved considerations other than cost optimization.

Fourth, there were several discrepancies between the actual and simulated distributions for military flights. Based on the fuel data, MAC flights departing Hickam for Travis should have preferred North route, but in practice Alfa was chosen most often. Also, the fuel data indicate that flight levels 350 and 370 should have been preferred by SAC flights, but in fact flight levels 310 and 330 were most favored. It is conceivable that constraints on military operations could account for the choice of nonoptimal tracks under some circumstances, but additional data would be required in order to reach a definite conclusion.

ECONOMIC BENEFIT RESULTS.

SYSTEM FUEL AND TIME PENALTY CALCULATION. A total of 30 simulation runs, each of 26 iterations of weekly traffic, were executed in order to evaluate the cost benefits of the proposed composite track system. Of the 30 runs, 10 runs each were made for the present, composite-above and composite-below systems. For each system, five levels of traffic were run for each of two weather conditions, summer and winter. The five levels were 100, 110, 120, 130, and 196 percent of present traffic.

In order to obtain more realism in the proximity calculations and a more realistic estimate of potential cost benefits of a composite system, the feature of the program that allows aircraft to request other than an optimal track was exercised in the 30 runs. Both route and flight level assignment for each aircraft type were altered for given percentages of time by terminal. Table 28 and 29 summarize the route and flight level changes that were made. The historical data indicated greater diffuseness in the winter than in the summer, accounting for more changes to the winter distribution. In two winter cases, the data indicated that the C141 and C5A should have preferred North route, but in actuality, Alfa was chosen. Therefore, in the simulation, the route preference order was reversed for these type aircraft. Fuel burn and flight time values were kept the same for these two aircraft types so that the first path preference was not the least costly.

Two penalty concepts are now introduced, and they must be carefully distinguished. The mean fuel burn (flight time) per aircraft, obtained through simulation for the present system, *minus the corresponding* quantity for the composite system is called the system-to-system penalty or more simply the penalty. On the other hand, for a given system the mean fuel burn (flight time) per aircraft, obtained through simulation, minus the mean fuel burn (flight time) per aircraft which would be obtained if every aircraft were to receive its first track preference, is called the within-system penalty or the relative penalty. Although the quantity of interest is the system-to-system penalty, previous work, including that of NAT/SPG, has considered the relative penalty, so results concerning the relative penalty are presented here as well for purposes of comparison.

The 10 penalty estimates for fuel burn and flight time for each composite system are shown in table 30 with a 95-percent confidence interval statement for each estimate. Values are normalized and are shown on a per aircraft basis rather than totals for ease of comparison.

Some aspects of the derivation of these results are now elaborated, along with a discussion of the relative penalties. Summations of fuel burn and flying time were compiled and updated as each additional aircraft receives a track assignment. The time summation using the scheduled flight time as the minimum allowable value to be tallied was compared to the straight summation of flight times for the summer 100 percent traffic level. It was found that using the scheduled time as a minimum value added less than 0.25 minutes to the flight time per aircraft. Since the two values were so close, comparisons are shown only for the actual flight time summation.

TABLE 28. SUMMER ROUTE CHANGES/FLIGHT LEVEL CHANGES

SUMMER

ROUTE CHANGES

B720	LAX→HNL	.5 Probability of being assigned South rather than Bravo
C141	HNL→LAX	.5 Probability of being assigned South rather than Bravo

ALTITUDE CHANGES

	SFO→HNL	LAX→HNL	HNL→SFO	HNL→LAX
B747	.20↑	.13↑	.30 ↓	.25↓
DC10	.66↓	.50↓	.66 ↓	.70↓
DC8	.16↑	.30↑	.16 ↑	.48↑
B707	.10↑	---	0.66↑	---
B720	---	---	---	---
KC135	---	---	---	---
C141	---	---	---	---
C5A	.33↑	.33↑	---	---

↑ = ALTITUDE ASSIGNMENT 4,000 FEET HIGHER
↓ = ALTITUDE ASSIGNMENT 4,000 FEET LOWER

TABLE 29. WINTER ROUTE CHANGES/FLIGHT LEVEL CHANGES

WINTER

ROUTE CHANGES

B747	HNL→SFO	.10 Prob. of North rather than Alfa
DC8	HNL→SFO	.10 Prob. of North rather than Alfa
---	HNL→LAX	.20 Prob. of South rather than Bravo
B720	LAX→HNL	.15 Prob. of South rather than Bravo
C141	LAX→HNL	Reversed route preference from Bravo to South
---	HNL SFO	Reversed route preference from North to Alfa
	HNL LAX	.25 South rather than Bravo
C5A	HNL SFO	Reversed route preference from North to Alfa
---	HNL LAX	.50 South rather than Bravo

ALTITUDE CHANGES

	SFO→HNL	LAX→HNL	HNL→SFO	HNL→LAX
B747	.22↑	.17↑	.29↓	.20↓
DC10	.35↓	.40↓	.45↓	.60↓
DC8	.55↓	.19↑	.32↑	.52↑
B707	.16↑	.18↓	.27↓	.19↓
B720	.15↓	.13↓	.08↑	---
KC135	.11↑	.50↓	.70↓	.75↓
C141	.39↓	.38↓	.09↑	.12↑
C5A	.23↑	.50↓	.38↓	---

↑ = ALTITUDE ASSIGNMENT 4,000 FEET HIGHER
↓ = ALTITUDE ASSIGNMENT 4,000 FEET LOWER

TABLE 30. PENALTY PER AIRCRAFT: FUEL BURN AND FLIGHT TIME

PENALTIES BETWEEN PRESENT AND COMPOSITE-ABOVE

Season	Traffic Level Percent of Present (1974)	95 Percent Confidence Interval For: Fuel Burn Penalty (pounds)	Flight Time Penalty (Minutes)
SUMMER	100	412 ± 21	0.61 ± .04
	110	436 ± 21	0.60 ± .04
	120	459 ± 21	0.64 ± .04
	130	465 ± 21	0.67 ± .04
	196 (1985 Forecast)	623 ± 21	0.63 ± .04
WINTER	100	378 ± 21	0.87 ± .04
	110	385 ± 21	0.87 ± .04
	120	394 ± 21	0.92 ± .04
	130	409 ± 21	0.89 ± .04
	196	557 ± 21	0.88 ± .04

PENALTIES BETWEEN PRESENT AND COMPOSITE-BELOW

Season	Traffic Level Percent of Present (1974)	Fuel Burn Penalty (pounds)	Flight Time Penalty (Minutes)
SUMMER	100	320 ± 22	1.28 ± .05
	110	351 ± 22	1.27 ± .05
	120	378 ± 22	1.34 ± .05
	130	398 ± 22	1.38 ± .05
	196	637 ± 22	1.41 ± .05
WINTER	100	293 ± 22	1.30 ± .05
	110	307 ± 22	1.33 ± .05
	120	323 ± 22	1.38 ± .05
	130	366 ± 22	1.37 ± .05
	196	523 ± 22	1.47 ± .05

By dividing the total fuel burn (flight time) by the number of aircraft receiving tracks, the fuel burn (flight time) per aircraft was obtained. For a given season and traffic level, the difference between the fuel burn (flight time) per aircraft for the present and composite systems is the penalty, as defined previously. In tables 31 to 34, the numerical results for both summer and winter are shown, along with the values of these quantities if each aircraft were to receive its first path preference (optimal path), and the consequent relative penalty for each system. The circled quantities are the system-to-system penalties. To the right of each circled quantity is the value the system-to-system penalty would have if all aircraft were to have received their first path preference. In other words, the composite system is advantageous not only because it lessens the cost of diversion for aircraft not receiving preferred paths on existing routes, but also because composite paths are oftentimes themselves the first preference. The importance of this contribution to the system-to-system penalty is measured by the ratios of the underlined quantities to the corresponding circled quantities. Contributions are greater in the composite-above case, indicating that the composite tracks are more often the first preference than in the composite-below system.

The relative penalties for the present system are consistently larger than the relative penalties for the composite systems in accord with intuition.

Looking again at tables 31 to 34, the optimim values for a given system would always be equal if the traffic mix were the same in each sample. A comparison of the size of the optimum values gives an indication as to which sample contained a mix of aircraft which burned more fuel. Note also that there is a trend in the system-to-system penalties as well as the relative fuel penalties as a function of traffic level.

An analysis of variance was performed on the results, and graphs for the best linear unbiased estimates for fuel burn and flight time were drawn as a function of traffic level. The graphs clearly show that the composite-above system yields a greater savings in fuel than the composite-below system. However, as would be expected, the composite-below system yields a greater savings in flight time. This occurs because the flight time decreases with a decrease in flight level. The average flight level in the composite-below system is obviously lower than in the composite-above system.

Statistical tests of the results indicate that there is a significant difference between each of the systems for flight time and that there is a significant difference between the composite systems and the present system for fuel burn. Tests do not show a significant difference for fuel burn between the composite-above and composite-below. However, examination of the fuel burn penalties shows that the composite above is always equal to or less than the composite-below value, thereby having to yield lower fuel burn values.

The analysis of variance shows that season and traffic level contribute statistically significant effects to fuel burn penalties. The season has a significant effect on flight time penalties for composite-above and both season and traffic level contribute significant effects to flight time penalty for composite-below.

TABLE 31. PENALTIES AND RELATIVE PENALTIES PER FLIGHT FOR SUMMER SEASON, COMPOSITE-ABOVE SYSTEM

Traffic Level Percent	System	(Fuel Burn (lb)) -	(Optimum Fuel Burn (lb)) =	(Relative Fuel Burn (lb))	(Flight Time (min)) -	(Optimal Flight Time (min)) =	(Relative Time Penalty (min))
	Present	78984	78539	445	292.76	291.52	1.24
100	Composite Above	78572	78288	284	292.15	291.41	0.74
	Difference	412	251		0.61	0.11	
	Present	79066	78564	502	292.97	291.48	1.29
110	Composite Above	78630	78313	317	292.17	291.37	0.80
	Difference	436	251		0.60	0.11	
	Present	79100	78550	550	292.92	291.56	1.36
120	Composite Above	78641	78299	342	292.28	291.45	0.83
	Difference	459	251		0.64	0.11	
	Present	79134	78500	634	294.10	292.66	1.44
130	Composite Above	78669	78302	367	293.43	292.54	0.89
	Difference	465	198		0.67	0.12	
	Present	79447	78449	998	293.20	291.55	1.65
196	Composite Above	78824	78824	598	292.57	291.44	1.13
	Difference	623	223		0.63	0.11	

TABLE 32. PENALTIES AND RELATIVE PENALTIES PER FLIGHT FOR SUMMER SEASON, COMPOSITE-BELOW SYSTEM

Traffic Level Percent	System	Fuel Burn (lb)	-	Optimum Fuel Burn (lb)	=	Relative Fuel Burn (lb)	Flight Time (min)	-	Optimal Flight Time (min)	=	Relative Time Penalty (min)
	Present	78984		78539		445	292.76		291.52		1.24
100	Composite Below	78664		78490		174	291.48		291.42		0.06
	Difference	320		49			1.28		0.10		
	Present	79066		78564		502	292.77		291.48		1.29
110	Composite Below	78715		78515		200	291.50		291.38		0.12
	Difference	351		49			1.27		0.10		
	Present	79100		78550		550	292.92		291.56		1.36
120	Composite Below	78722		78502		220	291.58		291.46		0.12
	Difference	378		48			1.34		0.10		
	Present	79134		78500		634	294.10		292.66		1.44
130	Composite Below	78736		78461		275	292.72		292.57		0.15
	Difference	398		39			1.38		0.09		
	Present	79447		78449		998	293.20		291.55		1.65
196	Composite Below	78810		78394		416	291.79		291.45		0.34
	Difference	637		55			1.41		0.10		

TABLE 33. PENALTIES AND RELATIVE PE[illegible] PER FLIGHT FOR WINTER SEASON, COMPOSITE-ABOVE SYSTEM

Traffic Level Percent	System	(Fuel Burn (lb)) -	(Optimum Fuel Burn (lb)) =	(Relative Fuel Burn (lb))	(Flight Time (min)) -	(Optimal Flight Time (min)) =	(Relative Time Penalty (min))
	Present	78681	78249	432	295.91	294.76	1.15
100	Composite Above	78303	78051	252	295.04	294.29	0.75
	Difference	$\boxed{378}$	198		$\boxed{0.87}$	0.47	
	Present	78648	78194	454	295.95	294.76	1.19
110	Composite Above	78263	77976	287	295.08	294.29	0.79
	Difference	$\boxed{385}$	218		$\boxed{0.87}$	0.47	
	Present	78786	78267	519	296.00	294.72	1.28
120	Composite Above	78392	78075	317	295.08	294.25	0.83
	Difference	$\boxed{394}$	192		$\boxed{0.92}$	0.47	
	Present	78832	78266	566	296.01	294.69	1.32
130	Composite Above	78423	78074	349	295.12	294.23	0.89
	Difference	$\boxed{409}$	192		$\boxed{0.89}$	0.46	
	Present	79043	78187	856	296.29	294.74	1.55
196	Composite Above	78486	77977	509	295.41	294.29	1.[illegible]2
	Difference	$\boxed{557}$	210		$\boxed{0.88}$	0.45	

TABLE 34. PENALTIES AND RELATIVE PENALTIES PER FLIGHT FOR WINTER SEASON, *COMPOSITE-BELOW SYSTEM*

Traffic Level Percent	System	(Fuel Burn (lb)) -	(Optimum Fuel Burn (lb)) =	(Relative Fuel Burn (lb))	(Flight Time (min)) -	(Optimal Flight Time (min)) =	(Relative Time Penalty (min))
100	Present	78681	78249	432	295.91	294.76	1.15
	Composite Below	78388	78194	194	294.61	294.50	0.11
	Difference	$\boxed{293}$	55		$\boxed{1.30}$	0.26	
110	Present	78648	78194	454	295.95	294.76	1.19
	Composite Below	78341	78138	203	294.62	294.50	0.12
	Difference	$\boxed{307}$	56		$\boxed{1.33}$	0.26	
120	Present	78786	78267	519	296.00	294.72	1.28
	Composite Below	78463	78228	235	294.62	294.46	0.1
	Difference	$\boxed{323}$	39		$\boxed{1.38}$	0.26	
130	Present	78832	78266	566	296.01	294.69	1.32
	Composite Below	78466	78219	247	294.64	294.43	0.19
	Difference	$\boxed{366}$	47		$\boxed{1.37}$	0.26	
196	Present	79043	78187	856	296.29	294.74	1.55
	Composite Below	78520	78134	386	294.82	294.50	0.32
	Difference	$\boxed{523}$	53		$\boxed{1.47}$	0.24	

Tables 35 and 36 show the percentage of aircraft receiving their first, or subsequent choice as a function of traffic level. It also shows the percentage of aircraft rejected by the system due to the unavailability of all five path preferences. These values also indicate a trend as a function of traffic level. The penalties for the aircraft rejected were included as if the aircraft had received its fifth preference. This is a conservative estimate as to the effect on the system, but the number rejected is so small that it does not significantly affect the average penalty.

ANNUAL PENALTY ESTIMATES. The annual penalty estimates are obtained first by multiplying the best estimates of the original system of summer and winter average penalties per aircraft from tables 31 and 33 by the average daily traffic for the respective seasons, giving a daily penalty. Multiplication by the number of days in each season, and summation of the winter and summer results gives the annual penalties. The composite-above system is used, since it shows the greater fuel savings. A monetary penalty is assigned solely on the basis of fuel consumption. Multiplication of the fuel penalty by the present fuel cost figure of (30¢ per gallon ÷ 6.77 lb per gallon = 4.43¢ per lb) yields the penalty in dollars.

		Cost (Dollars)	Fuel Burn (lb)	Flight Time (Minutes)
Mean Penalty per aircraft	Summer	\$18.26	412	0.61
	Winter	\$16.76	378	0.87
Mean Penalty per day	Summer	\$18.26 x 94 A/C/day) = \$1,716.44	(412 x 94) 38,700	(0.61 x 94) = 57.34
	Winter	(\$16.75 x 91 A/C/day) = \$1,524.25	(378 x 91) 34,400	(0.87 x 91) = 79.17
Penalty per year		\$591,400	13,341,000	24,900 minutes = 415 hours.

Two additional simulation runs, existing track system summer and composite-above summer, were made assuming that all aircraft adhered to the least costly fuel burn criteria for path selection. The purpose was to obtain a general idea of the potential savings between existing system operational policy and that of flying the composite-above track system with strict adherence to least cost path selection, and also to show the components of the savings; namely, savings from existing system procedures to using the existing track system with strict adherence to least cost and the savings between the existing and composite track system with strict adherence to least cost path selection.

TABLE 35. PERCENTAGE OF AIRCRAFT RECEIVING PATH PREFERENCE FOR SUMMER SEASON

SYSTEM PRESENT	LEVEL (Percent)	PATH PREFERENCE 1	2	3	4	5	Rejected
	100	81.98	15.76	1.85	0.38	0.03	0
	110	80.52	16.56	2.43	0.44	0.05	0
	120	79.05	17.72	2.64	0.50	0.09	0
	130	77.77	18.39	3.00	0.72	0.12	0
	196	68.91	22.49	5.44	2.26	0.71	0.19
COMPOSITE - ABOVE	100	85.61	12.94	1.25	0.19	0.01	0
	110	84.35	13.66	1.77	0.20	0.02	0
	120	83.28	14.51	1.95	0.22	0.04	0
	130	81.98	15.52	2.21	0.25	0.04	0
	196	73.68	19.92	4.77	1.15	0.36	0.12
COMPOSITE - BELOW	100	83.35	14.60	1.85	0.19	0.01	0
	110	81.98	15.36	2.41	0.21	0.04	0
	120	80.60	16.49	2.67	0.20	0.04	0
	130	79.31	17.35	3.05	0.26	0.03	0
	196	71.40	20.69	6.09	1.29	0.42	0.11

TABLE 36. PERCENTAGE OF AIRCRAFT RECEIVING PATH PREFERENCE FOR WINTER SEASON

SYSTEM PRESENT	LEVEL (Percent)	PATH PREFERENCE 1	2	3	4	5	Rejected
	100	81.92	16.06	1.68	0.29	0.05	0
	110	81.16	16.48	2.01	0.34	0.01	0
	120	79.26	17.80	2.37	0.51	0.06	0
	130	78.18	18.35	2.82	0.60	0.04	0.01
	196	70.82	22.35	4.69	1.65	0.42	0.07
COMPOSITE - ABOVE	100	86.51	12.17	1.20	0.11	0.01	0
	110	85.34	13.09	1.46	0.10	0.01	0
	120	83.78	14.19	1.82	0.18	0.03	0
	130	82.81	14.68	2.28	0.22	0.01	0
	196	76.12	19.20	3.72	0.10	0.22	0.04
COMPOSITE-BELOW	100	83.84	14.09	1.91	0.14	0.02	0
	110	83.14	14.47	2.21	0.17	0.01	0
	120	81.54	15.32	2.76	0.33	0.05	0
	130	80.57	15.91	3.20	0.30	0.02	0
	196	73.54	19.70	5.55	0.90	0.27	0.04

The average fuel burn per aircraft with strict adherence to least cost path selection for the existing track system was 78,901 pounds and for the composite track system 78,430 pounds. An estimate of the difference in total savings between present operational procedures and strict adherence for the composite system can be made by multiplying the estimated savings calculated on the previous page by the ratio of mean penalty per aircraft <u>with</u> strict adherence to mean penalty per aircraft <u>without</u> strict adherence.

$$\$591{,}400 \times \frac{(78{,}984 - 78{,}430)}{(78{,}984 - 78{,}572)} = \text{approx. } \$795{,}200$$

Of this, $\frac{(78{,}984 - 78{,}901)}{(78{,}984 - 78{,}572)} \times 591{,}400 = \text{approx. } \$119{,}100$ is attributable

to strict adherence to least cost route selection using the existing track system and indicates the potential savings possible under the existing track system.

This amount,

$$\frac{(78{,}901 - 78{,}430)}{(78{,}984 - 78{,}572)} \times \$591{,}400 = \$676{,}100$$

is the savings between flying the existing and composite track systems with strict adherence in both cases to least cost path selection.

<u>ALTERNATIVE ROUTE STRUCTURE ANALYSIS</u>. The flexibility of the simulation model and the flight plan data, spanning eight routes, made the analysis of various alternative route structures a relatively simple exercise. Analysis of the simulation by each terminal suggested that the Los Angeles-Honolulu and Honolulu-Los Angeles flights were accruing more penalty costs from optimum than the flights between San Francisco and Honolulu. Since the traffic was distributed nearly equally between each pair of terminals, balancing the penalties between each pair of terminals was expected to result in an overall reduction in fuel burn and consequently an increase in savings.

As a first step in the analysis, an upper bound of savings was calculated assuming that each aircraft would be able to fly the minimum path distance between terminals (great circle route between terminals) at its optimum cruise altitude.

After establishing the upper bound, various alternative route structures were studied by use of the simulation model with fuel burn data and associated path preferences being developed by interpolation from the fuel burn data on the eight routes for which flight plans were generated. By alternating regular and composite tracks, it was possible to move the Honolulu gateways further north for the Los Angeles routes, thus shortening the routes and balancing the penalties.

As a result of these studies, the route structure depicted in figure 5 and known as proposed composite track system B was found to be the most cost effective plan. In this plan, all the eastern gateways and the western gateways to the north remain essentially in the same locations, but the 3 southern gateways on the Hawaiian end are located approximately 55 nmi further north, thus straightening the southern routes and reducing the route distances. The moving of the gateways to the north is made possible by interchanging the regular and composite routes in the north. This changes Alfa and Bravo from a laterally adjacent route pair to a composite route pair. This accounts for the fact that in addition to being the most cost effective, the configuration also turns out to be the safest in terms of collision risk.

For aircraft maintaining constant altitude between gateways, the upper bound for fuel savings was calculated to be 32,920,000 lb per year at the traffic level which existed during the data collection period. At this traffic level, the savings resulting from the use of the proposed composite track system would be 30,248,000 lb per year or 91.9 percent of the maximum achievable.

As was done for the simple composite structure, the cost advantage of the proposed composite track system over the existing system was calculated as a function of traffic level. Cost calculations were performed using two values of fuel cost, one at 30¢ per gallon reflecting the present cost and one at 44¢ per gallon which is a projection of future fuel cost. Figure 6 shows the annual savings of the simple composite structure and the proposed composite over the existing system as a function of traffic level. For the traffic level of the data collection period, the simple composite system shows a yearly fuel savings of $591,400 and the proposed composite track system, a savings of $1,340,000 over the existing system at a fuel cost of 30¢ per gallon. At this level the savings using plan B are about 2.27 as great as the simple composite. At the same level the collision risk of the plan B structure is about one-fourth that of the existing system and one-half that of the simple composite system. As the traffic level increases the savings become even more pronounced as shown in figure 6. For example, if the traffic were to double, the cost savings of proposed composite over the existing system would increase by a factor of almost 2.5.

Since the routes serving Los Angeles are shorter in the proposed composite system, there would be an overall savings in flight time. The simple composite system showed an annual expected savings in flight time of 415 hours. The proposed composite track system showed an additional 1,215 hour savings, for a total expected savings of 1,630 flight hours per year at the data collection period traffic level.

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APPENDIX A

MATHEMATICAL DESCRIPTION OF COLLISION RISK ESTIMATION

This appendix presents the mathematical details of the derivation of the collision risk model applicable to the estimation of the expected number of accidents in 10 million track system flying hours due to the loss of all planned lateral, vertical, composite, and longitudinal separation. The first section of the appendix presents an overview of the collision risk model development. Next, the collision rate and resultant risk model forms for each of the four types of separation are derived. The third part of the appendix discusses approaches to the estimation of $P_y(L)$, the probability of lateral overlap of an aircraft pair initially separated by L nmi in the lateral domain. In the last section of the appendix, the theoretical derivation of lateral occupancy is presented, and the estimation of this quantity from data taken in an oceanic track system is discussed.

OVERVIEW OF COLLISION RISK MODEL DEVELOPMENT.

Under the assumptions of a parallel track system and no ATC loop errors, mid-air collisions may occur only because of imperfections of navigating and piloting, or flying errors, on the part of one or both members of an aircraft pair. The approach to the estimation of collision risk is to sum up the individual risks of collision to all aircraft due to these flying errors, in order to give the expected number of accidents (aircraft involved in collision) in the time period of interest, 10 million track system flying hours. Figure A-1 illustrates the general setting of an aircraft pair potentially exposed to the risk of collision. The intended or planned position of an aircraft is shown at "A." Surrounding A is an inner box of length $2S_x$, width $2S_y$, and height $2S_z$, with A located at distance S_x from either end of the box, S_y from either side, and S_z from the top and bottom. It should be clear that this box is in fact a representation of the imposition of ATC separation standards upon the aircraft located at A.

The flight-planned position of a second aircraft is shown at "B." A significant risk of collision between A and B will arise only when the planned position of B is on or very near to one of the faces of the inner box about A, and the risk will fall off very rapidly as the distance of B from the inner box increases. The second, outer box about A is called the proximity shell of A. For positions B outside this shell, the risk of collision between the two aircraft can be considered negligible, while for position B, within the proximity shell, two aircraft are said to be proximate and exposed to the risk of collision. The problem is to estimate the total risk of collision for all aircraft which will become proximate in the oceanic track system during 10 million flying hours. It is necessary, therefore, to take into account the expected number of times each aircraft has another aircraft in its proximity shell, the expected length of time this other aircraft will remain in the shell, and the path of this aircraft through the shell.

Figure A-2 shows the intended or planned position of two aircraft at A and B and the true positions at A' and B' resulting from flying errors. The collision risk between an aircraft pair is the chance that the time varying

separation vector $A'B'$ shrinks sufficiently such that the aircraft make metallic contact. This chance depends upon the intended separation vector AB and the flying errors committed by both aircraft. In the general case, both the intended position vector AB and the true position vector A'B' will be time dependent. The simplest representation of the positions of the two aircraft under study is in terms of components of motion (assumed to be independent of one another) along cartesian coordinates (x, y, z) corresponding to the along-track, crosstrack, and vertical dimensions. Assuming that each aircraft in the track system is the same size, and representing each aircraft as a box with sides λ_x, λ_y and λ_z corresponding to the aircraft's outer metallic dimensions, the collision process can be represented as the motion of one aircraft relative to the other, as is shown in figure A-3. In the figure, the intended positions of the two aircraft are shown as A and B, while the change in separation due to the combined flying errors of the two aircraft is shown by the vector BB". The box of length $2\lambda_x$, width $2\lambda_y$, and height $2\lambda_z$ with the centroid of the aircraft at position A midway between any two opposing faces is called the collision slab. Relative to the aircraft at point A within the collision slab, the collision process may be viewed mathematically as the entry of a particle, B, representing the second aircraft, into the collision slab. Defining the collision rate as the expected number of collisions per unit time between a pair of aircraft at some intended separation AB, the collision rate for the process shown in figure A-3 is the number of times the particle, shown at B", enters the slab through the top and bottom, the sides, and the ends. The collision rate for an aircraft pair is developed for a time period short enough such that the intended separation vector AB may be considered to be essentially constant. The frequency with which the particle B enters the slab through either end is obtained by multiplying the probabilities that particle B's y and z coordinates lie within the distances λ_y and λ_z of the center of the slab, P_y P_z, by the frequency N_x with which its x coordinate lies within λ_x of the center. For the constant intended separation (AB), this is written as:

$$(N_x P_y P_z)_{(AB)}$$

since it is assumed that flying errors of an aircraft are dimensionally independent and flying errors of proximate aircraft are independent.

Similarly, the frequency of entering through the top or bottom is

$$(N_z P_x P_y)_{(AB)}$$

and through either side is

$$(N_y P_x P_z)_{(AB)}$$

where P_x is the probability that B's x coordinate is within λ_x of the center of the slab, N_y is the frequency with which B enters the slab through the sides, and N_z is the frequency with which B enters the slab through the top or bottom.

Hence, the collision rate, $CR_{(AB)}$, for an aircraft pair during a time period sufficiently short that the intended separation, AB, may be assumed constant is given by:

$$CR_{(AB)} = (N_x P_y P_z)_{(AB)} + (N_y P_x P_z)_{(AB)} + (N_z P_x P_y)_{(AB)} \quad \text{(A-1)}$$

Equation A-1 must be evaluated for all possible intended separations, AB, planned for the aircraft pair during a transoceanic crossing and the individual contributions properly summed to give an overall collision rate for the crossing.

The calculation of the collision risk in each dimension then proceeds in a three-step process. First, the CR for a proximate aircraft pair is determined. Second, the average time, T, in which two aircraft are proximate during an oceanic crossing is determined. The product of these two quantities is the collision risk during an oceanic crossing, that is,

$$\text{Collision Risk} = CR \times T$$

The third step involves determining the expected number of accidents during 10 million track system flying hours, N_a. It is first necessary to divide T by H, the average number of flying hours over which the proximity was calculated, producing the average collision rate per hour of flight. This result is then multiplied by two in order to determine the average accident level per hour of flight (since each collision is counted as two accidents). Finally multiplication by 10 million hours results in the desired quantity, N_a. Thus,

$$N_a = 2\text{x}10^7(CR)\ (T/H) \quad \text{(A-2)}$$

Equation A-2 takes on a different functional form for each of the planned separations. The mathematical details of the derivations of the overall collision rate, CR, in A-2 for each of the planned separations are now presented.

MATHEMATICAL DERIVATION OF COLLISION RATE AND RISK.

The bombardment of the collision slab by particle B is now examined in more detail. Letting r represent x, y, or z, the frequency with which B's rth coordinate becomes less than λ_r is equal to the proportion of time that B's rth coordinate is less than λ_r, or P_r, divided by the average duration of this event. Letting t_r denote this average duration, the desired frequency, N_r, is:

$$N_r = \frac{P_r}{t_r} \quad \text{(A-3)}$$

Using equation A-3 in equation A-1, an alternative form of the collision rate can be obtained:

$$CR_{(AB)} = P_x P_y P_z \left(\frac{1}{t_x} + \frac{1}{t_y} + \frac{1}{t_z}\right) \quad \text{(A-4)}$$

Equation A-3 relates N_r to P_r. A second relationship between the two quantities is now developed. Let $G_{(AB)}(r,\dot{r})$ be the joint density function, for two aircraft with planned separation (AB), of relative velocity $\dot{r}$ and

relative separation r. Then $G_{(AB)}(r,\dot{r})dr d\dot{r}$ is the proportion of time that the separation in the rth dimension lies between r and r+dr and is changing at a rate beween $\dot{r}$ and $\dot{r}+d\dot{r}$. The time taken for a change in separation from r to r$\pm$dr in the rth dimension is:

$$\frac{dr}{\dot{r}}$$

From equation A-3, the average frequency with which the separation passes through the element (r, r+dr), when the velocity is in the range $\dot{r}$ to $\dot{r}+d\dot{r}$, is:

$$\frac{G_{(AB)}\ (r,\dot{r})dr d\dot{r}}{\frac{dr}{|\dot{r}|}} = |\dot{r}|\ G_{(AB)}\ (r,\dot{r})d\dot{r}$$

The total frequency of passing from r to r+dr is found by integrating over all possible values of $\dot{r}$:

$$\int_{-\infty}^{\infty} |\dot{r}|\ G_{(AB)}\ (r,\dot{r})d\dot{r}$$

In an interval of size $2\lambda_r$, $G_{(AB)}(r,\dot{r})$ will change very little. As a result, the total frequency of passing through the slab in the rth direction, $(N_r)_{(AB)}$, can be approximated by:

$$(N_r)_{(AB)} = \int_{-\infty}^{\infty} |\dot{r}|\ G_{(AB)}(o,\dot{r})d\dot{r} \tag{A-5}$$

A basic assumption of collision risk methodology is that r and $\dot{r}$ are independent. Thus, equation A-5 becomes:

$$(N_r)_{(AB)} = \phi_{(AB)}(0)\ \overline{|\dot{r}|} \tag{A-6}$$

where $\phi_{(AB)}(r)$ is the density function for r alone.

The probability of lateral overlap, $(P_r)_{(AB)}$, is the probability that $|r| \leq \lambda_r$. Thus:

$$(P_r)_{(AB)} = \int_{-\lambda r}^{\lambda r} \phi(r)dr \doteq \int_{-\lambda r}^{\lambda r} \phi(0)dr$$

or:

$$(P_r)_{(AB)} = 2\lambda_r\ \phi_{(AB)}\ (0) \tag{A-7}$$

Combining equations A-6 and A-7 results in:

$$(N_r(S_r))_{(AB)} = \overline{|\dot{r}(S_r)|}\ (P_r(S_r))_{(AB)}/2\lambda_r \tag{A-8}$$

where the planned separation in the rth dimension, S_r, is now explicitly stated. Combination of equation A-3 and A-8 results in the following relation:

$$t_r = \frac{2\ \lambda\ r}{\overline{|\dot{r}|}} \tag{A-9}$$

This result is quite in keeping with common sense, since it says that the average time spent by a particle within the collision slab is the length of the slab in the rth dimension divided by the particle's average speed.

Simplification of the expression for the collision rate, equation A-1, results when considering a rectangular track system. The planned separation in the lateral and vertical domain is constant throughout the track system, and thus it is only necessary to be concerned with the time varying nature of planned longitudinal separation. Equation A-1 then becomes:

$$CR_{(AB)} = (N_x)_{(AB)} P_y\ P_z + (P_x)_{(AB)} (N_y\ P_z + P_y\ N_z) \tag{A-10}$$

A collision in the rectangular track system will occur as a result of: (1) a loss of planned vertical separation between aircraft flying on the same route, (2) a loss of planned lateral separation between coaltitude adjacent route aircraft, (3) a loss of planned lateral and vertical separation between aircraft on adjacent composite routes, or (4) a loss of planned longitudinal separation between coaltitude same-route aircraft. The total collision risk is the sum of these four effects, which are assumed independent. Since the longitudinal risk requires special treatment, the derivation of its collision rate is postponed temporarily.

Let $(CR_y)_{(AB)}$ denote the collision rate due to the loss of planned lateral separation. Using equation A-10 and noting that the parameters of interest, the N's and P's, must be calculated by assuming planned separations of zero feet in the vertical domain and S_y nmi in the lateral, the lateral collision rate is given by:

$$\begin{aligned}(CR_y)_{(AB)} = {} & (N_x)_{(AB)} \left[P_y(S_y)\ P_z(0)\right] \\ & + P_{x(AB)} \left[P_y(S_y)\ N_z(0) + N_y(S_y) P_y(0)\right]\end{aligned} \tag{A-11}$$

Similarly, the vertical collision rate, $(CR_z)_{(AB)}$ is :

$$\begin{aligned}(CR_z)_{(AB)} = {} & (N_x)_{(AB)} \left[P_y(0)\ P_z(S_z)\right] \\ & + (P_x)_{(AB)} \left[P_y(0)\ N_z(S_z) + N_y(0)\ P_z(S_z)\right]\end{aligned} \tag{A-12}$$

In order to deal with the time varying nature of N_x and P_x induced by nonconstant planned longitudinal separations, the aggregate behavior of traffic is analyzed in a statistical manner. Because of the operational procedures involved in injecting aircraft into a rectangular track system, longitudinal separations between aircraft pairs are independent for adjacent tracks. If aircraft on adjacent tracks are proximate, the probability of overlap in the along-track direction is the ratio of the x dimension of the collision slab, $2\lambda_x$, to the x dimension of the proximity shell, $2S_x$, that is:

$$(P_x)_{(AB)} = \frac{\lambda_x}{S_x} \tag{A-13}$$

Using equations A-13 and A-8, the relative frequency of along-track penetrations of the collision slab is:

$$(N_x)_{(AB)} = \frac{\overline{|\dot{x}|}}{2S_x} \tag{A-14}$$

Substituting equations A-13 and A-14 into A-11 and A-12, the collision rates due to the loss of planned lateral and vertical separation are given by:

$$CR_y = \frac{1}{S_x}\left\{\frac{\overline{|\dot{x}|}}{2} P_y(S_y)\, P_z(0) + \lambda_x\, P_y(S_y)\, N_z(0) + \lambda_x\, N_y(S_y)\, P_z(0)\right\} \tag{A-15}$$

and

$$CR_z = \frac{1}{S_x}\left\{\frac{\overline{|\dot{x}|}}{2} P_y(0)\, P_z(S_z) + \lambda_x\, P_y(0)\, N_z(S_z) + \lambda_x\, N_y(0)\, P_z(S_z)\right\} \tag{A-16}$$

Because $\overline{|\dot{x}|}$ is the relative along-track velocity of an aircraft pair not assigned to the same track (lateral rate) or flight level (vertical rate), the directions of the aircraft must be taken into account. If the pair is flying in the same direction,

$$\overline{|\dot{x}|} = \overline{|\Delta V|} \tag{A-17}$$

where $\overline{|\Delta V|}$ is the average difference in the speeds of the aircraft. If the aircraft are flying in opposite directions,

$$\overline{|\dot{x}|} = 2\,\overline{V} \tag{A-18}$$

where $\bar{V}$ is the average speed of a typical track system aircraft. Substitution of these values for $\overline{|\dot{x}|}$ into equations A-15 and A-16 results in separate rate functions for same and opposite-direction flow.

In order to determine the rate of collision due to the loss of all planned composite separation in a system with composite tracks, an analysis similar to that which led to the lateral and vertical collision rates in equations A-15 and A-16 is performed. The only modification required is that the frequencies, N_y and N_z, and the probabilities of overlap, P_y and P_z, are evaluated at the combined planned lateral and vertical separations in the composite system, $S_y/2$ and $S_z/2$. The composite collision rate, CR_{yz}, is given by:

$$CR_{yz} = \frac{1}{S_x}\left\{\frac{\overline{|\dot{x}|}}{2} P_y(S_y/2)\, P_z(S_z(S_z/2) + \lambda_x\, P_y(S_y/2)\, N_z(S_z/2) + \lambda_x\, N_y\,(S_y/2)\, P_z(S_z/2)\right\} \tag{A-19}$$

The same considerations concerning the direction of flight of aircraft apply to CR_{yz} as to CR_y and CR_z.

Letting T_r(same) and T_r(opp) stand for the time which same and opposite direction aircraft pairs spend in proximity in dimension r, and denoting the same and opposite direction collision rates in the rth dimension by CR_r (same) and CR_r(opp), the collision risk associated with the rth planned separation is given by:

$$(\text{collision risk})_r = T_r(\text{same})CR_r(\text{same}) + T_r(\text{opp})CR_r(\text{opp})$$

The final quantity of interest in the collision risk analysis for the rth planned separation is N_{ar}, the expected number of accidents in 10 million track system flying hours due to the loss of all rth planned separation. Let H be the total number of track system flying hours during the period in which it was determined that there were T_r(same) and T_r(opp) hours of same and opposite direction proximity, respectively. The collision risk function of is converted to N_{ar} by:

$$N_{ar} = \frac{2\text{x}10^7}{H} (\text{collision risk})_r$$

Defining occupancy as the dimensionless quantity $E_r = (2T_r/H)$, N_{ar} is written as:

$$N_{ar} = 10^7 \text{ x } E_r(\text{same})CR_r(\text{same}) + E_r(\text{opp})CR_r(\text{opp}) \tag{A-20}$$

The expressions for N_{ay}, N_{az}, and N_{ayz}--the expected number of accidents in 10 million track system flying hours due to the loss of planned lateral, vertical, and composite separation, respectively--can now be given using equations A-15, A-16, A-19, and A-20 in conjunction with equations A-8, A-17, and A-18:

$$N_{ay} = 10^7 P_y(S_y) P_z(0) \frac{\lambda_x}{S_x}\left\{E_y(\text{same})\left[\frac{|\overline{\Delta V}|}{2\lambda_x} + \frac{|\overline{\dot{y}(S_y)}|}{2\lambda_y} + \frac{|\overline{\dot{z}(0)}|}{2\lambda_z}\right] + E_y(\text{opp})\left[\frac{\overline{V}}{\lambda_x} + \frac{|\overline{\dot{y}(S_y)}|}{2\lambda_y} + \frac{|\overline{\dot{z}(0)}|}{2\lambda_z}\right]\right\} \tag{A-21}$$

$$N_{az} = 10^7 P_y(0) P_z(S_z) \frac{\lambda_x}{S_x}\left\{E_z(\text{same})\left[\frac{|\overline{\Delta V}|}{2\lambda_x} + \frac{|\overline{\dot{y}(0)}|}{2\lambda_y} + \frac{|\overline{\dot{z}(S_z)}|}{2\lambda_z}\right] + E_z(\text{opp})\left[\frac{\overline{V}}{\lambda_x} + \frac{|\overline{\dot{y}(0)}|}{2\lambda_y} + \frac{|\overline{\dot{z}(S_z)}|}{2\lambda_z}\right]\right\} \tag{A-22}$$

$$N_{ay} = 10^7 P_y(S_y/2) P_z(S_z/2) \frac{\lambda_x}{S_x}\left\{E_{yz}(\text{same})\left[\frac{|\overline{\Delta V}|}{2\lambda_x} + \frac{|\overline{\dot{y}(S_y/2)}|}{2\lambda_y} + \frac{|\overline{\dot{z}(S_z/2)}|}{2\lambda_z}\right] + E_{yz}(\text{opp})\left[\frac{\overline{V}}{\lambda_x} + \frac{|\overline{\dot{y}(S_y/2)}|}{2\lambda_y} + \frac{|\overline{\dot{z}(S_z/2)}|}{2\lambda_z}\right]\right\} \tag{A-23}$$

Using equations A-8 and A-10, $(CR_x)_{(AB)}$, the rate of collision due to the loss of all planned longitudinal separation, can be written as:

$$(CR_x)_{(AB)} = \left[\frac{|\overline{\Delta V}|}{2\lambda_x} + \frac{|\overline{\dot{y}(0)}|}{2\lambda_y} + \frac{|\overline{\dot{z}(0)}|}{2\lambda_z}\right] P_y(0)\, P_z(0)\, (P_x)_{(AB)} \tag{A-24}$$

In the analysis of lateral, vertical, and composite collision rates, the independence of along-track separation for aircraft pairs on separate routes permitted discarding the dependence of P_x upon the planned separation vector (AB). However, in the case in which the aircraft pair are coaltitude on the same route, the dependence of P_x (AB) must be retained. Operationally, the second member of such a pair is not permitted to enter the track system until

some minimum time has elapsed since the entry of the lead aircraft. However, because the number of aircraft seeking entry to any track system is not sufficient to cause all same-route, coaltitude pairs to be separated initially by exactly the minimum time, the planned initial along-track separations in a track system may be considered to be random (within the constraint that they are all at least as large as the minimum).

Let $E_x(t)$ be the probability that a same-route coaltitude aircraft pair has exactly t minutes initial longitudinal separation after correction for mach number differences between the two aircraft. Further, let $P_x(t)$ be the probability that a same-route coaltitude aircraft pair loses exactly t minutes longitudinal spacing not explainable by mach number differences. Then, the probability density function describing longitudinal separation of an aircraft pair in the system is given by the convolution:

$$h(s) = \Sigma E_x(t)\ P_x(t-s)$$

where the summation extends over all possible values of initial separation, t. Longitudinal overlap will occur when the along-track time separation of the aircraft is within an interval centered at zero minutes, with width corresponding to $2\lambda_x$. Since the average speed, in knots, of a typical track system aircraft is $\bar{V}$, the endpoints of the interval are $\pm\lambda_x/\ (V \div 60)$. The $(P_x)_{(AB)}$ is determined by:

$$(P_x)_{(AB)} = 2\int_{-\lambda_x/(\bar{V} \div 60)}^{\lambda_x/(\bar{V} \div 60)} h(s)ds$$

where the 2 preceding the integral accounts for the possibility that the second aircraft of the pair will overtake the first or be overtaken by a folowing aircraft. Assuming that h(s) does not vary greatly over the limits of integration, $(P_x)_{(AB)}$ is given by:

$$(P_x)_{(AB)} \doteq \frac{4\ \lambda_x}{V/60}\ h(0) = \frac{4\ \lambda_x}{V/60}\ \Sigma E_x(t)\ P_x(t) \qquad \text{(A-25)}$$

Using equations A-24 and A-25, the expression for N_{ax}, the expected number of accidents in 10 million track system flying hours due to the loss of planned initial longitudinal separation, becomes:

$$N_{ax} = 2 \times 10^7 \left[\frac{|\overline{\Delta V}|}{2\lambda_x} + \frac{|\overline{\dot{y}(0)}|}{2\lambda_y} + \frac{|\overline{\dot{z}(0)}|}{2\lambda_z} \right] P_y(0)\ P_z(0) \times \frac{4\lambda_x \Sigma\ E_x(t)\ P_x(t)}{\bar{\bar{V}}/60} \qquad \text{(A-26)}$$

CALCULATION OF LATERAL OVERLAP PROBABILITY.

A parameter critical to the determination of N_{ay}, N_{ayz}, and N_{ax} is the probability of lateral overlap, $P_y(L)$, where L is S_y, $S_y/2$, or 0 depending upon the planned separation being investigated. In order to determine $P_y(L)$,

reference is made to figure A-4 which shows general probability density functions of cross-course error for two aircraft with planned lateral separation L. The probability that the center of aircraft No. 1 lies between Y and Y+dY is

$$f(Y)dY$$

The span of each aircraft in the y dimension is λ_y. Thus, the probability that aircraft No. 1 and aircraft No. 2 overlap, given that aircraft No. 1 is centered at Y, is the probability that aircraft No. 2 is centered between $Y-\lambda_y$ and $Y+\lambda_y$ which is given by:

$$\int_{Y-\lambda_y}^{Y+\lambda_y} g(W-L)dW$$

Then, since the cross-course errors of the two aircraft are independent, the probability that the two aircraft overlap at Y is:

$$f(Y)dY\int_{Y-\lambda_y}^{Y+\lambda_y} g(W-L)dW$$

The probability of lateral overlap $P_y(L)$ is then obtained by integrating this expression over all possible values of Y, that is:

$$P_y(L) = \int_{-\infty}^{\infty} f(Y)\int_{Y-\lambda_y}^{Y+\lambda_y} g(W-L)dWdY$$

Under the assumptions (1) that g(Y-L) is essentially constant over in interval of width $2\lambda_y$, and (2) that the density functions of the two aircraft are identical, the probability of lateral overlap is given by:

$$P_y(L) = 2\lambda_y \int_{-\infty}^{\infty} f(Y) \quad f(Y-L)dY \qquad \text{(A-27)}$$

that is, the probability is the self-convolution of the probability density function of lateral errors, multiplied by a constant.

Observations of lateral errors in both the NAT and CEP track systems have consistently demonstrated that the vast majority of lateral deviations from course are relatively small in magnitude and certainly less than $S_y/2$. However just as consistently observed has been the phenomenon of a non-zero proportion of deviations at least as large as $S_y/2$. Furthermore, there does not appear to be a single distributional form which can characterize the overall distribution of errors. As a result, f(Y) is modeled in two parts: (1) the body or core of the distribution defined between $-S_y/2$ and $S_y/2$ and (2) the tail defined from $S_y/2$ to ∞ and from $-\infty$ to $-S_y/2$.

Analysis of the copious core data collected in both the CEP and NAT track systems has indicated that a First Laplacian (or two-sided exponential) distribution is a good characterization of the body of f(Y). The form of f(Y) in the core is thus:

$$f(Y) = 2\lambda)^{-1}\exp(-|Y|/\lambda)$$

(A-28)

where λ equals $\sigma / 2$, and σ is the standard deviation of the distribution of lateral deviations from course.

The difficulties in modeling f(Y) exist in a proper characterization of the shape and area of the tail. In his development of collision risk analysis theory, Reich (references 1, 2, and 3) considered three possible shapes for the tail: (1) the "pessimistic spike" which places the entire tail area at the center of the adjacent track, (2) the "level tail," which is a rectangular distribution between $S_y/2$ and Y*, a value of Y slightly larger than S_y and chosen to maximize the self-convolution of f(Y), and (3) the "exponential decay." Figure A-5 displays these tail shapes for an assumed tail area of β.

The form of $P_y(L)$ for the values of L which are of interest is now presented using equation A-27. For $L=S_y$, $P_y(L)$ is the probability of lateral overlap for coaltitude aircraft on adjacent routes. For the three tail shapes of figure A-5, $P_y(S_y)$ takes on the following forms:

(1) "pessimistic spike"

$$P_y(S_y) = \sqrt{2}\,\beta\lambda_y/\sigma, \quad \lambda_y << \sigma$$

(2) "level tails"

$$P_y(S_y) = \frac{\lambda_y\beta}{Y-S_y/2}\left[1 - 1/2 \exp\left(-\sqrt{2}(S_y-Y)/\sigma\right)\right]$$

(3) "exponential decay"

$$P_y(S_y) = \frac{\sqrt{2}\,\lambda_y k \exp(-S_y k)}{\sigma} \quad X$$

$$\left\{\frac{1 - \exp\left(S_y k/2-S_y/\sqrt{2}\sigma\right)}{\sqrt{2}/\sigma \quad k} + \frac{1}{\sqrt{2}/\sigma + k}\right\}$$

For $L=S_y/2$, $P_y(L)$ is the probability of lateral overlap for two aircraft on adjacent composite routes. In this case, the shape and area of the tail of f(Y) is not particularly important, since the core-core interaction in the self-convolution predominates. Neglecting the contribution of the tails of f(Y), the expression for $P_y(S_y/2)$ using equation A-28 is:

$$P_y(S_y/2) = \frac{\lambda_y(S_y + \sqrt{2}\sigma)\exp}{2\sigma^2}\left[-S_y/(\sqrt{2}\sigma)\right]$$

For L=0, $P_y(L)$ is the probability of lateral overlap for two aircraft assigned to the same route. As in the case of $L=S_y/2$, only the shape of the body of f(Y) has impact upon the lateral overlap probability. The expression for $P_y(0)$ using equation A-28 is:

$$P_y(0) = \frac{\lambda_y}{\sqrt{2}\,\sigma}, \quad S_y >> \sigma$$

DERIVATION OF EXPRESSION FOR LATERAL PROXIMITY TIME AND OCCUPANCY.

Two aircraft are laterally proximate if they are coaltitude, assigned to laterally adjacent routes and within a distance S_x of each other longitudinally. A cross section of a typical rectangular track system is shown in figure A-6. The $(i,j)^{th}$ track has associated with it a flow rate of m_{ij} aircraft per hour. The average number of aircraft on the $(i-1,j)^{th}$ track is:

$$\frac{m_{i-1,j}}{\overline{V}}$$

where $\overline{V}$ is the average velocity of the aircraft. Then, for a given aircraft on track (i,j) the number of aircraft on track (i-1,j) that are proximate to that aircraft is given by:

$$\frac{2S_x\, m_{i-1,j}}{\overline{V}}$$

The transit time through an L nmi length track system is $L/\overline{V}$. Thus, the number of $(i-1,j)^{th}$ track aircraft proximate to a given $(i,j)^{th}$ track aircraft on a total trip basis is:

$$\frac{2S_x\, m_{i-1,j}}{\overline{V}} \cdot \frac{L}{\overline{V}}$$

Multiplying this result by m_{ij} yields the total number of proximate pairs existing between route i and i-1 on flight level j:

$$\frac{2LS_x\, m_{i-1,j}\, m_{ij}}{\overline{V}^2}$$

Summing this result over all laterally adjacent routes for all altitudes yields $\dot{T}_y$, the total number of proximate pairs in the track system per hour of flight:

$$\dot{T}_y = \frac{2LS_x}{\overline{V}^2} \sum_{i=2}^{t} \sum_{j=1}^{r} m_{i-1,j}\, m_{ij}$$

Letting H represent the total number of track system flying hours during which lateral proximity time is to be calculated, the expressions for the lateral proximity time, T_y(same) and T_y(opp), of same and opposite-direction aircraft pairs are given by:

$$T_y(\text{same}) = \frac{2HLS_x}{\overline{V}^2} \sum_{\substack{\text{same level adjacent} \\ \text{routes same-direction} \\ \text{traffic}}} \sum m_{i-1,j}\, m_{ij} \qquad \text{(A-29)}$$

$$T_y(\text{opp}) = \frac{2HLS_x}{\bar{V}^2} \sum_{\substack{\text{same level adjacent} \\ \text{routes opposite-} \\ \text{direction traffic}}} \sum m_{i-1,j}\, m_{ij} \qquad \text{(A-30)}$$

The same and opposite-direction occupancies, $E_y(\text{same})$ and $E_y(\text{opp})$, are obtained by multiplying $T_y(\text{same})$ and $T_y(\text{opp})$ by $2/H$. In the estimation of occupancy for a track system based upon flight progress information obtained in the track system, approximations to (A-29) and (A-30) are made. Typically, flight progress information for several days in the track system is examined in the estimation process. For each of the days, the longitudinal reporting times of all aircraft are examined to determine the number of aircraft pairs which were proximate in the sense described at the beginning of this section. The count of such pairs is multiplied by 2 and divided by the number of aircraft which flew during the day under scrutiny and this ratio is used as the estimate of occupancy for that day. The occupancy estimates for all days are then examined in the aggregate, and an attempt is made to infer the trend in occupancy as a function of traffic count on the days analyzed.

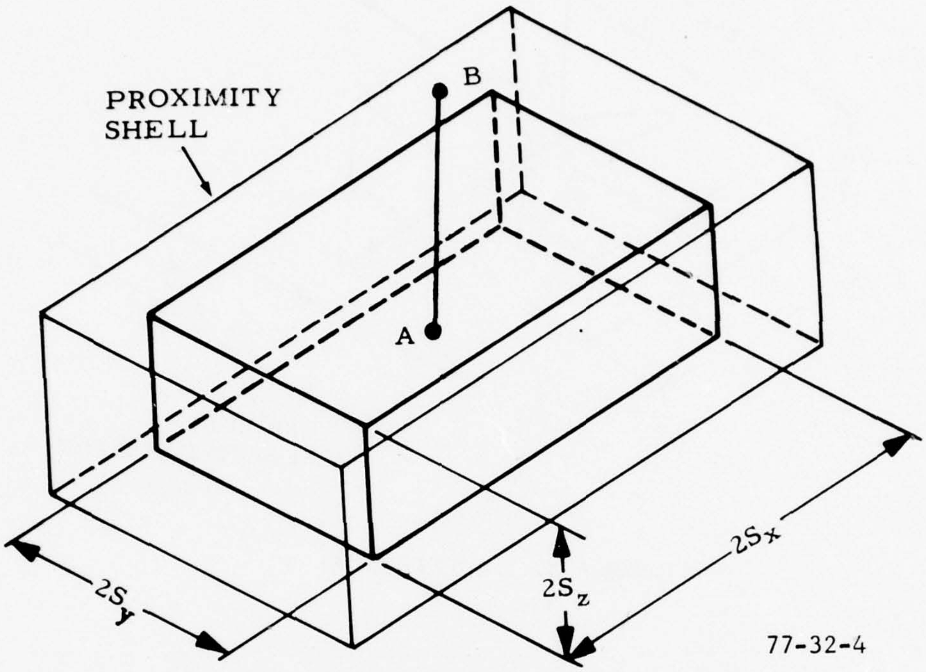


FIGURE A-1. EXPOSURE TO RISK

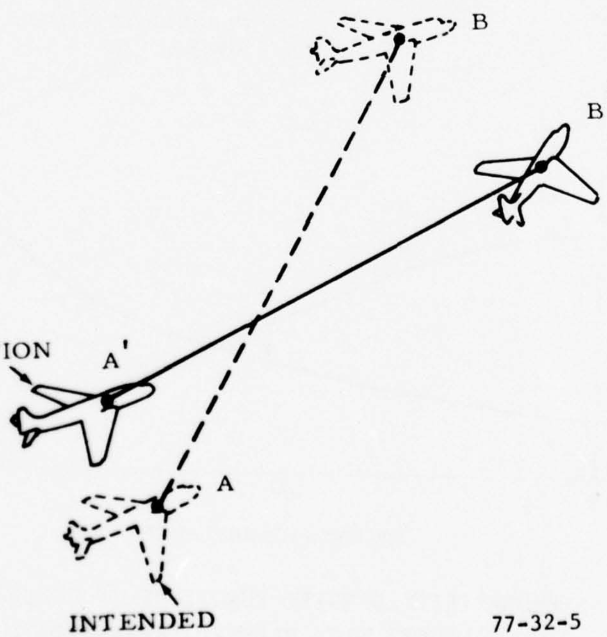


FIGURE A-2. SEPARATION VECTORS

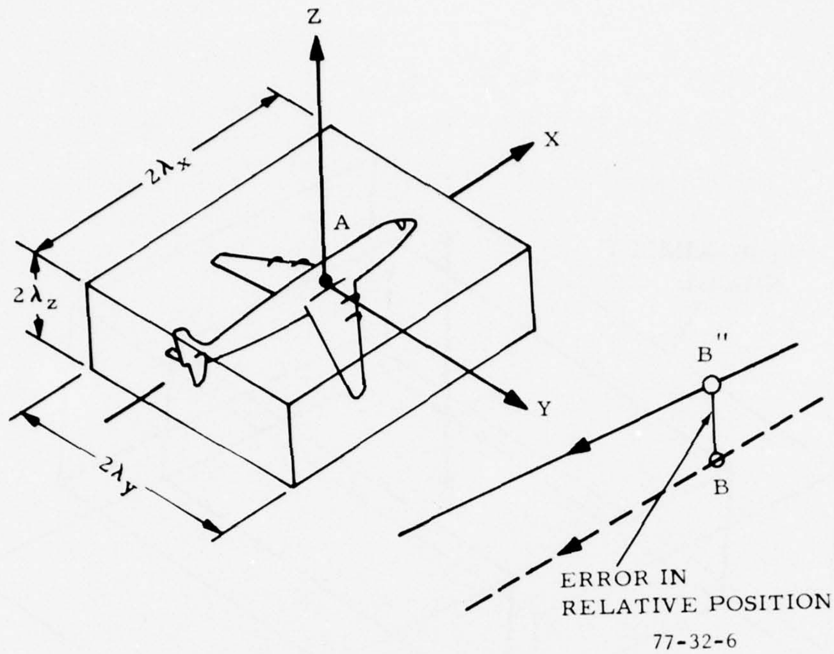


FIGURE A-3. COLLISION SLAB

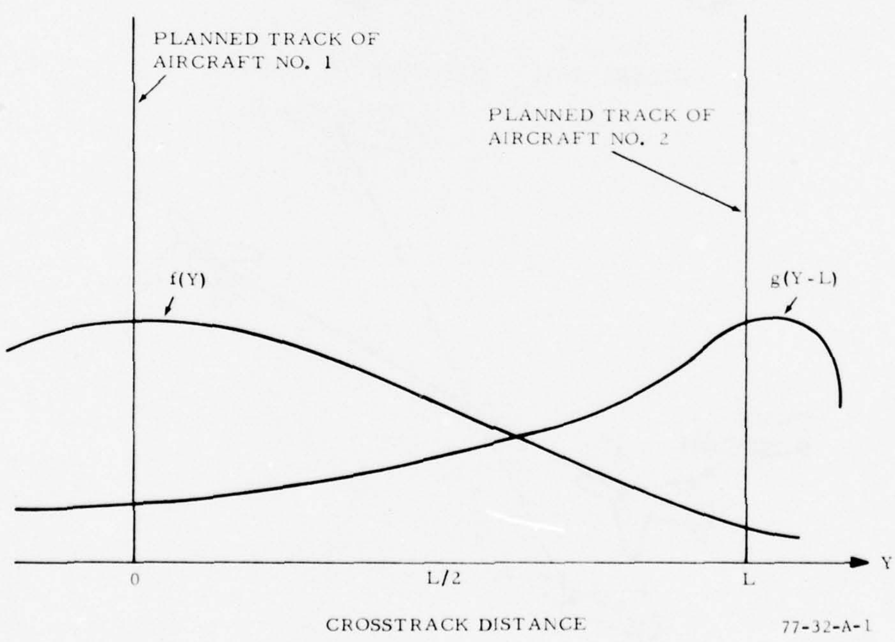
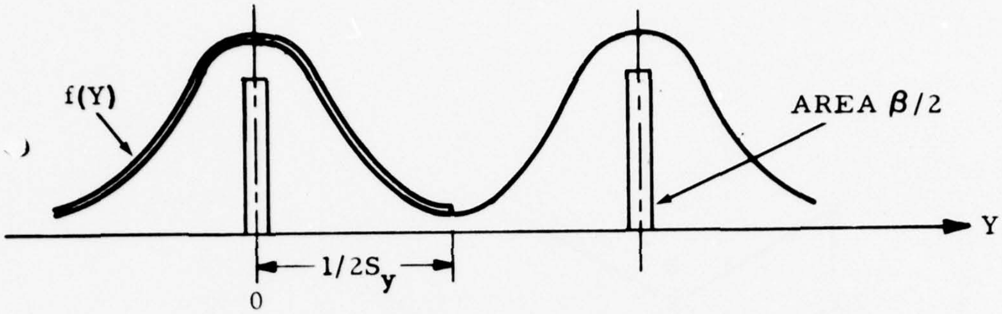
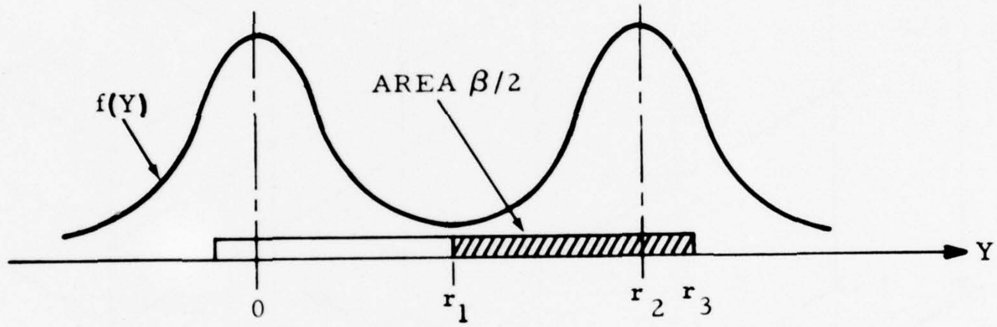


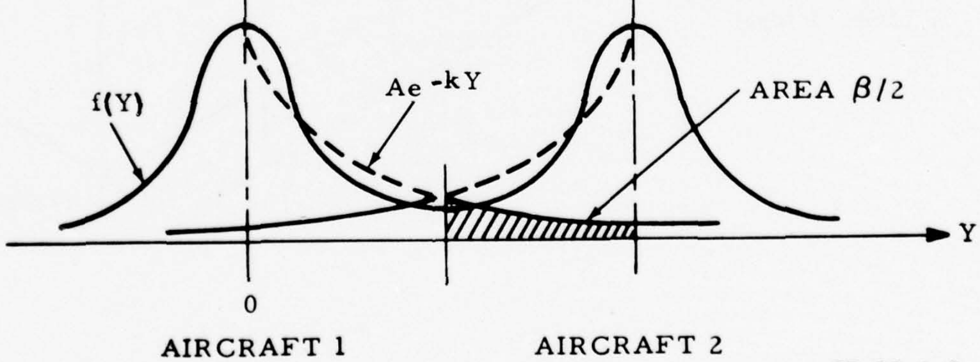
FIGURE A-4. PROBABILITY DENSITY FUNCTIONS OF CROSS-COURSE ERROR FOR TWO AIRCRAFT WITH PLANNED SEPARATION L



(a) "PESSIMISTIC SPIKE" ASSUMPTION



(b) "LEVEL TAILS" ASSUMPTION



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(c) "EXPONENTIAL DECAY" ASSUMPTION

FIGURE A-5. ALTERNATIVE ASSUMPTIONS OF TAIL SHAPE

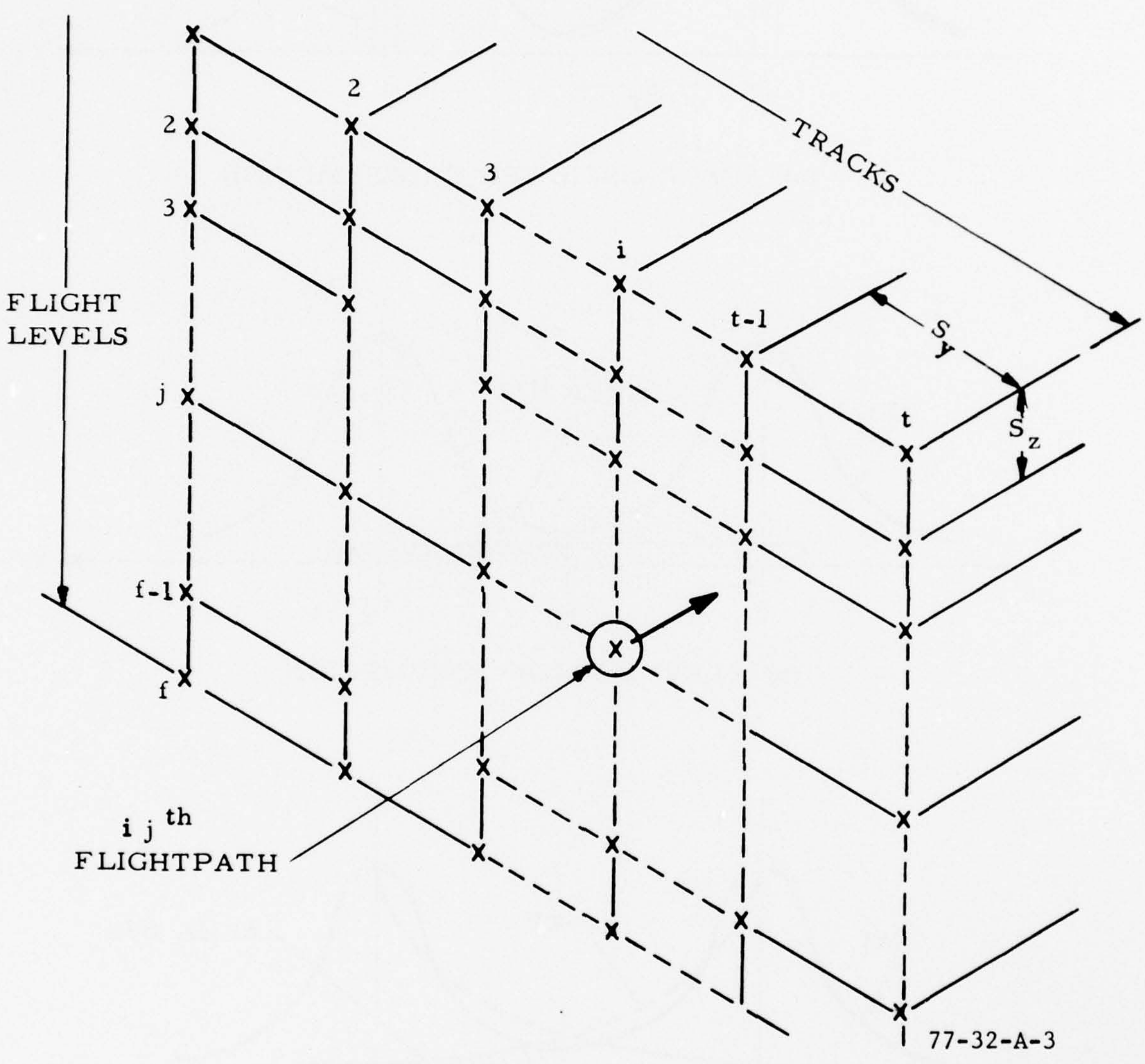


FIGURE A-6. TYPICAL CROSS-SECTION OF RECTANGULAR TRACK SYSTEM

APPENDIX B

DESCRIPTION OF CEP DATA COLLECTION

The calculations of collision risk estimates for the longitudinal, lateral, vertical, and composite dimensions are performed using mathematical models developed by the NAT/SPG. Certain parameters in these models must be estimated using data collected in the oceanic track system under study. In order to obtain these data as well as information necessary to characterize the track system's environment and ability to respond to user demands, a data collection was carried out in the CEP from December 15, 1973, to June 30, 1974. The sources of information relevant to collision risk analysis and environment characterization were three:

(1) Flight crew survey forms.
(2) ATC facility data.
(3) Aircraft position measurements.

The type of information provided by these sources as well as the methods of obtaining these data are described below.

FLIGHT CREW SURVEY FORMS.

Figure B-1 illustrates a form distributed to flight crews in the CEP in order to both collect information for which there was no other source and also to provide information useful in cross-checking other resources. The following statement was printed on the reverse side of the form:

"The Systems Research and Development Service of the Federal Aviation Administration is conducting an evaluation of the merit of applying composite separation procedures in the track system between the mainland of the USA and Hawaii. Composite separation is used in the North Atlantic track system and provides, by a combination of lateral and vertical separations, increased freedom in the assignment of desirable flight levels. The objective of this program is to quantitatively justify a more efficient system for your use without degradation of the operational safety.

Information on flight operations in the existing track system is being collected at FAA ground and shipboard based facilities. It is essential that these data be supplemented by information that is only available to the aircraft pilot. We vitally need the participation of all users. You are urged to complete the form on the other side for each flight conducted in all or part of the Hawaii/Mainland track system during the test period.

The data collection is to be conducted for a six-month period ending June 30, 1974.

If any flight crew member of an aircraft involved in a navigational deviation files this report during the period of this program regarding the

deviation, the Administrator will take no enforcement or other adverse action, remedial or disciplinary, against any of the flight crew members of the aircraft for navigational deviations revealed by this report, even though a violation of the Federal Aviation Regulations may be disclosed."

Data in Block 8, "Flight Plan Information" requested that the flight crew indicate the altitude and route preferred for the CEP crossing and also note if the desired flight plan was able to be followed. This information was of great import in determining if the CEP track system was able to respond to user requests.

During the 6 1/2-month period, 54.2 percent of the observed flights returned Flight Crew Survey Forms. It is felt that this sampling, while not as large as desired, did reasonably represent the population of users of the CEP. A comparison of the forms returned to the system user profile obtained from other sources does not indicate any significant biasing with respect to specific operators, aircraft types, or routes utilized.

Table B-1 represents a summary of the various navigational systems used in the CEP as determined from the flight crew survey forms. As expected, the percent in use totals to more than 100, since many flights used more than one system. Also included in the table are equipment failure statistics. Only one complete INS system failure was reported. Many of the Doppler NAV and Doppler (Sensor Only) system failures were reported as intermittent or partial. All LORAN A failures occurred on commercial flights, while all but one of the LORAN C, celestial and CONSOLAN failures were reported by military flights.

TABLE B-1. NAVICATION SYSTEMS REPORTED AS USED ON CEP FLIGHT CREW SURVEY FORMS

Navigation System	Percent of Sample	Percent of Failures
INS	58.2	1.3
Doppler NAV System	33.9	6.7
Doppler (Sensor Only)	11.6	7.6
LORAN C	12.8	8.4
LORAN A	27.4	1.7
Celestial	21.3	.08
Consolan	30.7	.03

ATC FACILITY DATA.

In order to estimate certain critical parameters used in the calculation of collision risk, an attempt was made to gather ATC records of all flights in the CEP during the data collection period. These data, originally on flight progress strips, were collected independently in the Honolulu and Oakland ARTCC oceanic sectors, since each center had some information on all flights in the CEP. This redundance in data collection virtually eliminated the possibility of missing any flights. It was also possible to gather transcripts of oceanic communications between ATC facilities and flights aloft in the CEP as a further source for identifying aircraft using the track system.

The ATC facility data, supplemented by the Flight Crew Survey Forms and oceanic communication transcripts mentioned above, was sorted and transcribed into a form suitable for automatic data processing. This compendium of information relative to CEP aircraft was termed the Flight History File. The file contained data useful not only for the assessment of collision risk, but also for the analysis of potential economic benefits engendered by the application of composite separation. Within the file, each flight for which data existed was made a separate entry. The information for each entry is the aircraft flight identifier and type, the transponder code employed during the flight, the direction of flight as well as the route requested and assigned, the requested and assigned altitude and any altitude changes made enroute. In addition, the aircraft's filed or assigned mach speed and the times reported at longitudinal reporting points are recorded, as well as the type of navigation system used by the aircraft. Finally, an estimate of lateral deviation from course when the flight is inbound to landfall, as made by a radar traffic controller, is included in the Flight History File entry for each aircraft.

AIRCRAFT POSITION MEASUREMENTS.

Estimation of important parameters in the collision risk models require that aircraft position measurements, describing the navigational ability of aircraft, be available. These position measurements, utilizing secondary surveillance radar, were made at five locations in the CEP during the data collection period. The locations were the Oakland, Los Angeles, and Honolulu ARTCC's, as well as at a special mobile radar installation configured at Pahoa on the Island of Hawaii and aboard OSV November in the middle of the routesystem.

The ideal method of radar position measurement is the automatic processing and recording of returns from each aircraft of interest by a special purpose data acquisition system. Such systems were used aboard the OSV and, for a substantial portion of the data collection period, at Pahoa and Honolulu. Because of possible interference with automated ATC systems in the heavy traffic environment of the West Coast, it was operationally impossible to install data acquisition systems at the Oakland and Los Angeles ARTCC's.

In order to obtain as large a sample of aircraft position measurements as possible and to overcome the loss of any data because of failures in data acquisition systems, radar controllers at the Honolulu, Los Angeles, and

Oakland ARTCC's monitored CEP aircraft at first radar contact inbound to landfall from the route system and manually recorded an estimate of the flight's lateral deviation from course. The manual measurements were made to a granularity of 1 nmi and reflected a tendency of the data takers to quantize lateral deviations in 5-nmi increments. Since these manual measurements formed the larger portion of the lateral deviation estimates obtained during CEP data collection and since refined estimates of collision risk require data of a smoother nature, the controller observed lateral deviations from course were smoothed using automatically recorded data.

The sources of these automatically recorded measurements in Hawaii were the data acquisition systems installed in February 1974 at Pahoa and Honolulu. These systems continued to record aircraft track data until the end of the collection program in June 1974.

The controller measurements from Oakland and Los Angeles were calibrated using track data automatically recorded by the National Airspace System (NAS) automated ATC facilities at these centers. This data was collected throughout the 6 1/2-month period.

PROCESSING OF LATERAL DEVIATION MEASUREMENTS. Since there were over 15,000 observations made by the manual method and since these observations were recorded to the nearest nautical mile, measurements recorded by the automatic method were used to calibrate these data to a finer granularity for collision risk estimation. Those aircraft which had both a manual and automatic lateral deviation estimate such that the automatic measurement was made within 1 minute of the manual observation were identified for each ARTCC. The set of such manual measurements for each center was compared to the overall set of manual deviation measurements for the center. The histograms of all manually made measurements are presented in tables B-2 and B-3. For each center, it was statistically determined that the set was a representative sample of the overall deviation measurement histogram within the limits of 20 nmi north deviation to 20 nmi south, an interval which encompasses the bulk of the measurements. The distribution of the automatic measurements was then used to represent the manual measurements in this interval. Manual measurements outside this interval remained in the histogram, unless they could be replaced by radar measurements.

The manual and automatic measurements showed good agreement. Certain trends noted in the manual data were verified in the automatic. The Oakland manual measurements showed a slight bias to south of course, which was supported by automatic data. The Honolulu manual data, on the other hand, showed a bias to north of course. This bias was confirmed by automatic measurements and may be caused by aircraft anticipating reclearance to domestic routes in the Honolulu area.

The means of the automatic data measurement sets from the West Coast were small in magnitude and were taken to be zero. While the mean of the Hawaiian automatic data deviations was determined to be approximately 2 nmi north, it was taken as zero in the risk calculations for computational convenience and

TABLE B-2. MANUAL DEVIATIONS NORTH OF COURSE

Deviation From Course (nmi)	Center			Total
	Oakland	Los Angeles	Honolulu	
110	1	0	0	1
80	1	0	0	1
75	0	1	0	1
70	1	1	0	2
65	1	0	0	1
60	1	0	1	2
55	0	0	1	1
45	0	1	2	3
40	1	2	4	7
35	1	1	4	6
30	4	6	1	11
25	6	4	1	11
21-24	1	2	3	6
20	4	19	56	79
16-19	0	1	14	15
15	14	18	96	128
11-14	8	10	47	65
10	46	69	379	494
6-9	34	38	229	301
5	102	115	763	980
1-4	102	77	633	812
0	1942	3464	5450	10856

TABLE B-3. MANUAL DEVIATIONS SOUTH OF COURSE

Deviation From Course (nmi)	Center			Total
	Oakland	Los Angeles	Honolulu	
80	1	0	1	2
75	0	0	1	1
70	1	0	0	1
60	0	1	0	1
55	1	0	1	2
50	5	3	0	8
45	0	1	0	1
40	5	0	5	10
35	3	0	1	4
30	3	4	6	13
25	9	7	7	23
21-24	2	1	3	6
20	12	10	22	44
16-19	1	1	4	6
15	42	18	40	100
11-14	19	4	11	34
10	204	52	104	360
6-9	166	43	41	258
5	372	102	134	608
1-4	318	71	96	485

because the bias may be attributable to anticipation of clearances rather than navigation errors. The mean of the shipboard measurements was also close to zero.

INVESTIGATION OF GROSS NAVIGATION ERRORS. The estimate of lateral collision risk based upon data collected in an oceanic system is very sensitive to the number of large cross-course navigation errors observed. In order to verify such errors reported in the CEP manual measurements, a committee composed of representatives of the users and providers of the ATC system in the CEP investigated each report of lateral deviation from course which was at least 30 nmi. The numbers of such reports investigated was 96 and the results of the investigations are summarized here.

The committee sought information from the operators of the 96 flights identified as potential gross deviations from course. No data were received concerning 14 of the 96 potential errors, and these 14 were accepted as true and left in the data set.

An attempt to categorize the remaining 82 deviations was then made by the committee. The results of this analysis were:

Crew Errors	57
Equipment Failure	11
Weather Problems	1
Reclearance by ATC prior to deviation report	10
No Traceable Explanation	3

The 10 error reports indicated as occurring after ATC reclearance to a new route were deleted from the data set. Of the three reports indicated as having no traceable explanation, one was removed from the data set after examination of automatic data from two independent sources indicated a deviation from course of less than 30 nmi.

A further analysis of equipment failures associated with the gross navigation errors is presented in table B-4. Navigation system equipment failures are shown by type, and in the cases in which more than one system type failed for a flight, equal weight has been assigned to the failure of each type. Thus, the failures of both a LORAN A system and a Doppler NAV system during a single flight would each have weight 1/2.

An analysis of shipboard lateral deviation data was made in order to ascertain the correlation of large final course deviations with midcourse errors. Data collection systems installed aboard two vessels, which together served a total of four periods as OSV November during the interval December 15, 1973, to June 30, 1974, had the maximum potential of providing lateral deviation data on CEP flights for 79 days, or 40.7 percent of the data collection period. Of the 85 final course gross deviations reported and validated during the data collection period, 38 occurred during the previously mentioned 79 days. Radar data sufficient to positively identify the aircraft and compute lateral

deviation from course statistics was obtained for 20 of the potential maximum of 38 flights for which final course gross deviations were recorded. Table B-5 summarizes the reasons for failing to observe the remaining 18 aircraft. As can be seen from the table, two-thirds of the aircraft for which there are no measurements flew at times when either the shipboard radar or data collection system was inoperative. All but one of these 12 occurrences took place during the first or fourth station periods, the first period during which one or the other of the two Coast Guard vessels used in the data collection interval was fitted with data collection systems. Midcourse deviation measurements for three additional aircraft were not obtained, since these aircraft flew at times during which the OSV was off station on search-and-rescue operations, and hence were not within radar coverage. No radar track was recorded for three aircraft, as is noted in the table, although these aircraft flew when both the data collection system was operative and the OSV was on station. These three aircraft flew within a 5-day period, and two flew the same day. This perhaps indicates that a noncatastrophic problem existed with the data collection system at this time.

Table B-6 presents a comparison of the midcourse and final lateral deviations of the 20 aircraft reported as large final course lateral deviations during OSV on-station periods. Because of the limited sample size of the data in table B-6, caution should be exercised when deducing information about the relationship of midcourse and final deviations.

TABLE B-4. EQUIPMENT FAILURES ASSOCIATED WITH CEP GROSS NAVIGATION ERRORS REPORTS

Navigation System	Number of Failures
INS	2
Doppler	17 1/3
LORAN A	1 1/2
LORAN C	9 5/6
Computer	4 5/6
Radio Altimeter	13 2/3
Compass	1 5/6
TOTAL	51

TABLE B-5. ANALYSIS OF MISSING MIDCOURSE RADAR TRACKS WITH LARGE FINAL COURSE DEVIATIONS

	OSV STATION PERIOD				TOTAL
Reason Aircraft Track Not In Sample	I	II	III	IV	
Data Collection System and/or Radar Failure	7	1	0	4	12
Ship Off-Station During Station Period	0	1	0	2	3
Aircraft Tracks Not In Recorded Radar Data	0	0	3	0	3
Total	7	2	3	6	18

TABLE B-6. COMPARISON OF REPORTED LARGE FINAL COURSE DEVIATIONS WITH OBSERVED MIDCOURSE DEVIATIONS

Final Course Deviation	Mid-Course Deviation
30 South	5 South
30 South	8 North
30 South	23 South
30 South	30 South
30 South	31 South
30 North	9 North
30 North	10 North
30 North	25 North
35 South	41 South
37 North	100 North
40 South	2 South
40 South	35 South
40 South	36 South
40 South	37 Scuth
45 North	40 South
50 South	35 South
50 South	55 South
60 South	25 South
70 North	2 North
74 North	10 North

DEPARTMENT OF TRANSPORTATION - FEDERAL AVIATION ADMINISTRATION

SEPARATION EVALUATION — HAWAII / MAINLAND ORGANIZED TRACK SYSTEM

Form Approved: OMB No. 04–S73038
Approval Expires 6–30–74

1. Assigned Enroute Transponder Code	2. Aircraft Type	3. Registration No.	4. Flight No. or Call Sign (*NW 78; MAC-234*)

5. Departure Gateway ('X' one box only)

WEST	EAST
☐ Neptune	☐ Maple
☐ Agate	☐ Apricot
☐ Banana	☐ Cypress
☐ Schooner	☐ Yucca
☐ ________ (*Specify*)	☐ ________ (*Specify*)

6. GMT Date and Time at Departure Gateway

Month and Day (Dec.24; Jan. 11)	Time

7. GMT when reaching initial cruise flight level

8. Flight Plan Information

	Route	Flight Level	Approved	Not Approved
Filed				
Assigned				
Changes Requested Enroute				

9. Navigational Equipment (*Complete Appropriate Boxes*)

Type	Number Installed A	Systems Used for Tracking B	Auto-Pilot Coupled C Yes	Auto-Pilot Coupled C No	Equipment Failures Enroute D	GMT of Failure E
INS						
Doppler NAV System						
Doppler (Sensor only)						
Loran C						
Loran A						
Celestial						
Consolan						
Radio Altimeter (High range)						
Other (Specify)						

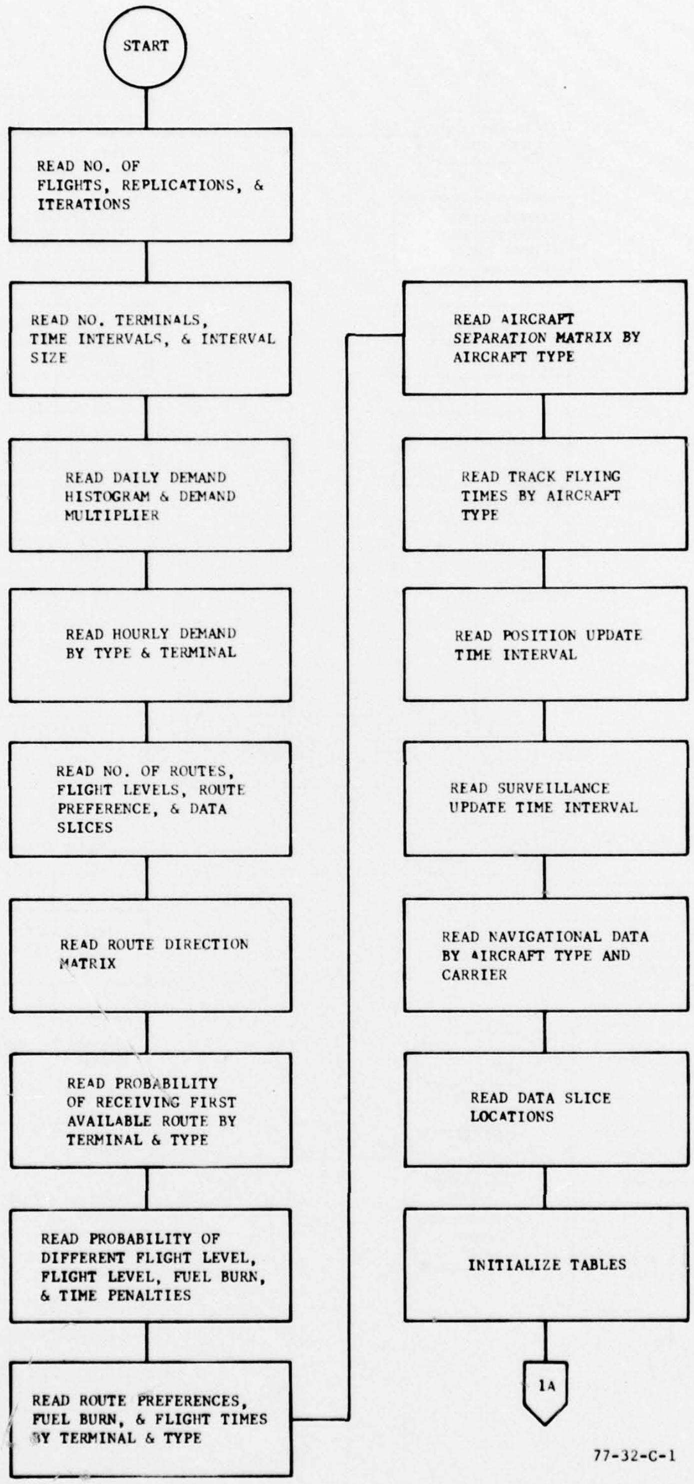
10. Was equipment, for which failure was indicated in Item 9D in use as a primary track keeping reference ☐ Yes ☐ No

FAA Form 9800-6 OT (11-73) **(Use expires 6/30/74)**

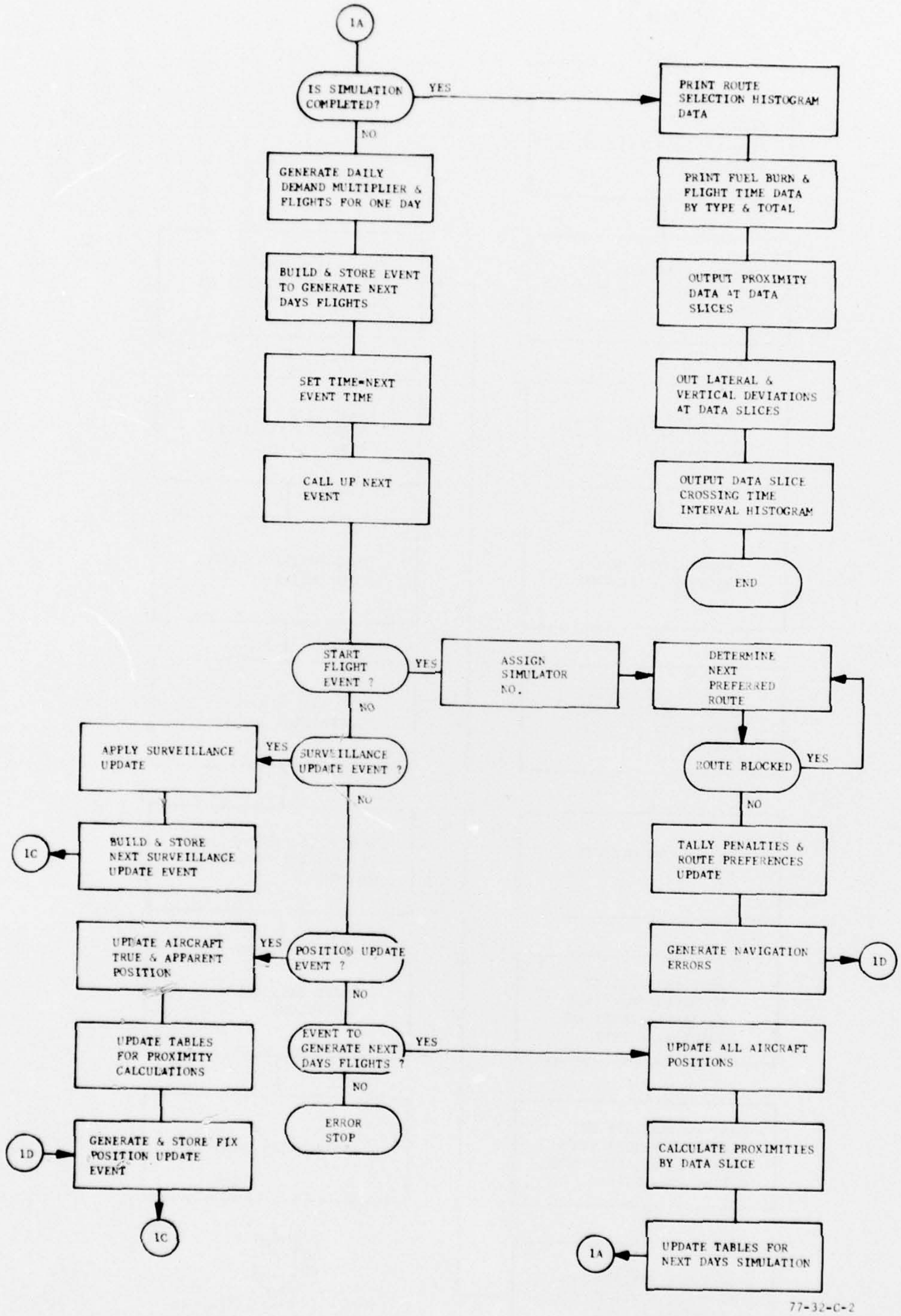
FIGURE B-1. FLIGHT CREW SURVEY FORM

APPENDIX C

FLOW DIAGRAM OF CEP SIMULATION MODEL


START
READ NO. OF FLIGHTS, REPLICATIONS, & ITERATIONS
READ NO. TERMINALS, TIME INTERVALS, & INTERVAL SIZE
READ DAILY DEMAND HISTOGRAM & DEMAND MULTIPLIER
READ HOURLY DEMAND BY TYPE & TERMINAL
READ NO. OF ROUTES, FLIGHT LEVELS, ROUTE PREFERENCE, & DATA SLICES
READ ROUTE DIRECTION MATRIX
READ PROBABILITY OF RECEIVING FIRST AVAILABLE ROUTE BY TERMINAL & TYPE
READ PROBABILITY OF DIFFERENT FLIGHT LEVEL, FLIGHT LEVEL, FUEL BURN, & TIME PENALTIES
READ ROUTE PREFERENCES, FUEL BURN, & FLIGHT TIMES BY TERMINAL & TYPE
READ AIRCRAFT SEPARATION MATRIX BY AIRCRAFT TYPE
READ TRACK FLYING TIMES BY AIRCRAFT TYPE
READ POSITION UPDATE TIME INTERVAL
READ SURVEILLANCE UPDATE TIME INTERVAL
READ NAVIGATIONAL DATA BY AIRCRAFT TYPE AND CARRIER
READ DATA SLICE LOCATIONS
INITIALIZE TABLES
1A

77-32-C-1


1A
IS SIMULATION COMPLETED?
YES
NO
PRINT ROUTE SELECTION HISTOGRAM DATA
GENERATE DAILY DEMAND MULTIPLIER & FLIGHTS FOR ONE DAY
PRINT FUEL BURN & FLIGHT TIME DATA BY TYPE & TOTAL
BUILD & STORE EVENT TO GENERATE NEXT DAYS FLIGHTS
OUTPUT PROXIMITY DATA AT DATA SLICES
SET TIME=NEXT EVENT TIME
OUT LATERAL & VERTICAL DEVIATIONS AT DATA SLICES
CALL UP NEXT EVENT
OUTPUT DATA SLICE CROSSING TIME INTERVAL HISTOGRAM
END
START FLIGHT EVENT ?
YES
ASSIGN SIMULATOR NO.
DETERMINE NEXT PREFERRED ROUTE
NO
APPLY SURVEILLANCE UPDATE
YES
SURVEILLANCE UPDATE EVENT ?
ROUTE BLOCKED
YES
NO
NO
BUILD & STORE NEXT SURVEILLANCE UPDATE EVENT
1C
TALLY PENALTIES & ROUTE PREFERENCES UPDATE
UPDATE AIRCRAFT TRUE & APPARENT POSITION
YES
POSITION UPDATE EVENT ?
GENERATE NAVIGATION ERRORS
1D
NO
UPDATE TABLES FOR PROXIMITY CALCULATIONS
EVENT TO GENERATE NEXT DAYS FLIGHTS ?
YES
UPDATE ALL AIRCRAFT POSITIONS
NO
ERROR STOP
1D
GENERATE & STORE FIX POSITION UPDATE EVENT
CALCULATE PROXIMITIES BY DATA SLICE
1C
1A
UPDATE TABLES FOR NEXT DAYS SIMULATION
77-32-C-2